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Artificial Closed Ecosystems, Life Support Systems & Industrial Ecology. Synergies of terrestrial and space R&D as drivers for implementing sustainability

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FACULTÉ DES GÉOSCIENCES ET DE L'ENVIRONNEMENT
INSTITUT DES DYNAMIQUES DE LA SURFACE TERRESTRE

Artificial Closed Ecosystems, Life Support Systems & Industrial Ecology

Synergies of terrestrial and space R&D as drivers for implementing sustainability

THÈSE DE DOCTORAT

présentée à la

Faculté des géosciences et de l'environnement
de l'Université de Lausanne

pour l'obtention du grade de

Docteur en sciences de l'environnement
(PhD in Environmental Sciences / Studies)

par

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Titulaire d'un
MAS en Environnement-Sciences, Ingénierie et Management de l'Environnement de l'EPFL
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intitulée

ARTIFICIAL CLOSED ECOSYSTEMS, LIFE SUPPORT SYSTEMS AND INDUSTRIAL ECOLOGY. SYNERGIES OF TERRESTRIAL AND SPACE R&D AS DRIVERS FOR IMPLEMENTING SUSTAINABILITY.

Lausanne, le 05 avril 2022

Marie Elodie Perga

Pour le Doyen de la Faculté des géosciences et de l'environnement

Professeure Marie-Elodie Perga

To my parents and my wife,

To my kids and my family,

To all my friends and colleagues.

ABSTRACT

This PhD thesis focuses on the convergence of two main research domains – industrial ecology (IE) and life support systems (LSS) –, a convergence that is further examined in the context of development of artificial closed ecosystems (ACE). An ACE is a simplified and miniaturised ecosystem operating in closed-loop. It uses biological organisms (bacteria, microalgae, plants, animals, etc.) to regenerate air, water and food with the objective of complete self-sufficiency. An ACE replicates and shortens some of Earth's biogeochemical cycles and accelerates nutrient and resource recycling loops that occur in the terrestrial environment. In this research, integrated LSS are considered as 'crewed' ACE – that is ACE with humans – designed to ensure health, safety and minimal comfort in extreme environments so that humans can survive in autonomy in confined and isolated habitats over prolonged periods of time. The succession of LSS compartments (e.g. bioreactors, plant growth chambers) are combined to meet the human needs and achieve an uninterrupted conversion and regeneration of organic wastes such as exhaled carbon dioxide, urine, feces and non-edible parts of plants into breathable atmosphere, potable water and edible biomass. Advanced LSS or space ACE are required for long-term manned space missions or habitations, when terrestrial resupply is logistically not possible or too costly. Space ACE are designed to ensure the required environment for humans to sustain life in outer space habitats over prolonged periods of time.

The first part of this thesis attempts to clarify the potential, relevance and interest of ACE research in order to consolidate the conceptual foundations of IE. Key concepts for ACE analysis in the perspective of IE are proposed, concepts that encompass interactions on artificially predefined symbioses in circular systems, as well as cycling, biodiversity, compartmentalisation, reproduction and evolution. By leveraging the study of integral recycling loops in the context of an expanding society and a world of finite resources, ACE are considered as relevant tools for the maturation of industrial ecosystems. When operating under the radical conditions of the space context, a space ACE can be envisioned as a model for industrial ecosystems under extreme constraints. All in all, this study demonstrates that ACE development represents an excellent compromise and has an untapped potential for developing further the theoretical basis of IE.

The second part focuses on the possible ways to cross-fertilise the terrestrial and space dimensions of LSS development. The performed research covers the conceptualisation of R&D synergies within the Oïkosmos programme and the exploitation of an ACE ground demonstrator as a technology platform for the study of ACE. It shows how such full-scale crewed demonstrator for preparing manned planetary exploration in the most realistic conditions can leverage and intensify LSS development by providing research synergies at the interface of its terrestrial and space dimensions. In particular, this thesis provides various case studies related to European Space Agency's MELiSSA project on circular systems, as well as to the Swiss-based start-up Earth Space Technical Ecosystem Enterprises SA which develops ACE-related components, prototypes and applications.

The third part of this work tackles the contributions of ACE development to the operationalisation of IE. This dissertation analyses the potential of ACE for the technological empowerment of self-sufficient habitat on Earth and for the implementation of terrestrial sustainability. The examined Earth-based applications of ACE include decentralised waste valorisation and resource recovery combined to on-site food production, measurement of exposures (including food, drugs, micropollutants, etc.) and analysis of their effects on the health and on the environment, e.g. indoor air quality control (biological and chemical risks), at-home health monitoring and remote assistance, and maintaining of the quality of life and well-being of habitat occupants. In the context of the emergence of New Space, this thesis also highlights that the next frontier for sustainability is space and considers the possible ways to envisage sustainability (in the human life perspective) at cosmic scale.

ACE and LSS are eye-openers to the benefits of bioinspiration. They open up new avenues for the control and regulation of ecosystems leading to new facets of interpreting nature and the improvement of health in general within a closed habitat. It can be deduced from this work that the realisation of the promises of ACE development will depend on an open and constructive dialogue between medicine, biology, humanities and environmental sciences, enabled by engineering and digitalisation capacities.

Even if manned long-duration and remote space missions would not be carried out, research for hyper-efficient space ACE is worth doing anyway not only due to the growing constraints on Earth, but to their

potential for the sustainable resource management on Earth. This research anticipates that ACE components will be developed in any case for their relevance for terrestrial sustainability, and their market applicability into everyday life.

As evidenced by this thesis, research on ACE and LSS is an excellent instrument to forge a sustainable future, by elaborating more closed industrial ecosystems, more sustainable in the face of decreasing supplies of raw materials and increasing problems of waste and pollution. Therefore, synergies of terrestrial and space R&D on ACE and LSS can act as drivers for implementing sustainability, in the perspective of IE.

RÉSUMÉ

Cette thèse de doctorat se concentre sur la convergence de deux domaines de recherche principaux – l'écologie industrielle (EI) et les systèmes de support-vie (SSV) –, une convergence qui est examinée plus précisément dans le contexte du développement des écosystèmes clos artificiels (ECA). Un ECA est un écosystème simplifié et miniaturisé fonctionnant en circuit fermé. Il utilise des organismes biologiques (bactéries, microalgues, plantes, animaux, etc.) pour régénérer l'air, l'eau et la nourriture afin d'atteindre une autosuffisance complète. Un ECA reproduit et raccourcit certains des cycles biogéochimiques de la Terre, et accélère les boucles de recyclage des nutriments et des ressources qui surviennent dans l'environnement terrestre. Dans cette recherche, les SSV intégrés sont considérés comme des ECA avec équipage, conçus pour assurer à ses habitants la santé, la sécurité et le confort minimal dans des environnements extrêmes pour qu'ils puissent survivre en autonomie dans des habitats confinés et isolés durant des périodes prolongées. La succession des compartiments de support-vie (bioréacteurs, chambres de croissance de plantes, etc.) est combinée pour répondre aux besoins de l'homme et réaliser une conversion et une régénération ininterrompues des déchets organiques tels que le dioxyde de carbone expiré, l'urine, les excréments et les parties non comestibles des plantes, respectivement en atmosphère respirable, eau potable et biomasse comestible. Les SSV avancés ou ECA spatiaux sont nécessaires pour réaliser des missions spatiales habitées de longue durée, dont le réapprovisionnement terrestre n'est logistiquement plus possible ou devient trop coûteux, et sont conçus pour assurer l'environnement nécessaire et maintenir en vie des humains au sein d'habitats spatiaux.

La première partie de cette thèse vise à clarifier le potentiel, la pertinence et l'intérêt de la recherche sur les ECA afin de consolider les fondements conceptuels de l'EI. Des concepts clés pour l'analyse de l'ECA dans la perspective de l'EI sont proposés, ceux-ci englobant les interactions basées sur des symbioses prédéfinies artificiellement au sein de systèmes circulaires, ainsi que les concepts de cyclisation, de biodiversité, de compartimentation, de reproduction et d'évolution. En s'appuyant sur l'étude des boucles de recyclage intégral dans une société en expansion et un monde où certaines ressources sont devenues limitées, les ECA sont considérés comme des outils pertinents pour la maturation des écosystèmes industriels. Lorsqu'il fonctionne dans les conditions radicales de l'espace, un ECA spatial peut être envisagé comme un modèle d'écosystèmes industriels soumis à des contraintes extrêmes. Dans l'ensemble, cette étude démontre que le développement d'ECA représente un excellent compromis et offre un potentiel inexploité pour développer davantage la base théorique de l'EI.

La deuxième partie se concentre sur les moyens possibles de fertilisation croisée des dimensions terrestres et spatiales du développement des SSV. La recherche effectuée couvre la conceptualisation des synergies de R&D dans le cadre du programme Oïkosmos et l'exploitation d'un démonstrateur au sol d'ECA comme plateforme technologique pour l'étude des ECA. Elle montre comment un tel démonstrateur grandeur nature, doté d'un équipage et destiné à préparer l'exploration planétaire habitée dans les conditions les plus réalistes, peut avoir un effet de levier et intensifier le développement de SSV en établissant des synergies de recherche à l'interface de ses dimensions terrestres et spatiales. En particulier, cette thèse fournit diverses études de cas liées au projet MELiSSA de l'Agence spatiale européenne sur les systèmes circulaires, et à la start-up suisse Earth Space Technical Ecosystem Enterprises SA (ESTEE) qui développe des composants, prototypes et applications basés sur les ECA.

La troisième partie de ce travail aborde les contributions du développement des ECA à l'opérationnalisation de l'EI. Elle analyse le potentiel des ECA pour le développement technologique d'habitats autosuffisants sur Terre et pour la mise en œuvre de la durabilité terrestre. Les applications terrestres relatives aux ECA examinées comprennent la valorisation décentralisée des déchets et la récupération des ressources combinées à la production alimentaire sur site, la mesure des expositions (y compris les aliments, les médicaments, les micropolluants, etc.) et l'analyse de leurs effets sur la santé et l'environnement, par exemple pour le contrôle de la qualité de l'air intérieur (risques biologiques et chimiques), la surveillance de la santé à domicile et la téléassistance, ainsi que le maintien de la qualité de vie et du bien-être des occupants d'un habitat. Dans le contexte de l'émergence du New Space, cette thèse met également en lumière que la prochaine frontière pour la durabilité est l'espace et considère les moyens possibles d'envisager la durabilité à l'échelle cosmique.

Les ECA et SSV sont des révélateurs des bénéfices de la bioinspiration. Ils ouvrent de nouvelles voies pour le contrôle et la régulation des écosystèmes débouchant sur de nouvelles facettes d'interprétation de la nature, et pour l'amélioration de la santé au sein d'habitat clos. On peut déduire de ce travail que la réalisation des ambitions liées au développement d'ECA dépendra du dialogue ouvert et constructif entre la médecine, la biologie, les sciences humaines et environnementales, facilité par l'ingénierie et la digitalisation.

Même si des missions spatiales habitées de longue durée et distance ne devaient pas être réalisées, la recherche sur les ECA spatiaux hyper efficients vaut la peine d'être menée, non seulement en raison des contraintes croissantes sur Terre, mais aussi du fait de leur potentiel pour la gestion durable des ressources sur Terre. Cette recherche anticipe que les composants d'ECA seront développés dans tous les cas pour leur pertinence en termes de durabilité terrestre, et leur application commerciale dans la vie quotidienne.

Comme le démontre cette thèse, la recherche sur les ECA et les SSV offre un excellent instrument pour forger un avenir durable, en élaborant des écosystèmes industriels davantage fermés, et plus durables face à la diminution des approvisionnements en matières premières et aux problèmes croissants liés à la gestion des déchets et à la pollution. Par conséquent, les synergies de la R&D terrestre et spatiale sur les ECA et les SSV peuvent agir comme des catalyseurs de la mise en œuvre de la durabilité, dans la perspective de l'EI.

EXECUTIVE SUMMARY

Context of the PhD thesis and research framework

The present work fits within the context of the following major trends:

- The development of the field of industrial ecology, in the broader context of research and development in the area of sustainability (including circular economy, cleaner production, sustainable consumption, etc.);
- The development of habitats demonstrating high levels of material closure and self-sufficiency (tiny house, off-grid habitat, autarkic habitat, etc.), as well as featuring proper conditions for a healthy habitat (telework; telehealth, especially for elderly people), in particular with the COVID-19 sanitary crisis of 2020-2021 and its wide implications in terms of biosafety;
- The growing production of organic and locally sourced food with high nutritional value and the advancement of agriculture in confined space (including vertical/urban farming or 3D-agriculture);
- The development of eco-innovation (or responsible innovation), including new business models (product service systems, mHealth, etc.);
- The advancement of life support systems for space purposes, and their associated Earth-based applications, in the context of the emergence of New Space;
- The recent and spectacular development of the disciplinary fields of systems biology and 'omics' sciences (including metabolomics, microbiomics and nutrigenomics);
- The ubiquitous trend of digitalisation, in particular in relation to the fields of information and communication technologies (but also Industry 4.0, smart cities, etc.), artificial intelligence, (Big) Data management and e-Health.

Until recently, the above-listed trends and themes were characterised by their different origins, distinct evolutions and own development trajectories. One of the objectives of this thesis is to show how they built on increasing convergences.

Convergence of the research domains of IE and LSS

Among such a wealth of topics, this thesis focuses more specifically on the convergence of two main research domains – industrial ecology (IE) and life support systems (LSS) –, a convergence that is further examined in the context of development of closed systems, namely 'artificial closed ecosystems' (ACEs).

An ACE is a simplified and miniaturised ecosystem operating in closed-loop. It uses biological organisms (bacteria, microalgae, plants, animals, etc.) to regenerate air, water and food with the objective of complete self-sufficiency. As an artificial set-up, an ACE encapsulates and interfaces a selection of engineered pieces of ecosystemic elements. It replicates and shortens some of Earth's biogeochemical cycles, and thus accelerates nutrient and resource recycling loops that occur in the terrestrial environment. In this research, integrated LSS are considered as 'crewed' ACE – that is an ACE with humans – designed to ensure health, safety and minimal comfort in extreme environments so that humans can survive in autonomy in confined and isolated habitats over prolonged periods of time. The succession of LSS compartments (e.g. bioreactors, plant growth chambers) are combined to meet the human needs and achieve an uninterrupted conversion and regeneration of organic wastes such as exhaled carbon dioxide, urine, feces and non-edible parts of plants into breathable atmosphere, potable water and edible biomass. Advanced LSS or space ACE are required for long-term manned space missions or habitations, when terrestrial resupply is logistically not possible or too costly. Space ACE are designed to ensure the required environment for humans to sustain life in outer space habitats over prolonged periods of time.

The choice of studying ACE along the axes of IE and LSS research domains is based on the strong convergence of their development trajectories since the late 1990s/early 2000s. On one hand, this work analyses ACE in the perspective of the domain of IE, and, on the other hand, in the perspective of the experimental framework of LSS, which constitute the two main axes of this research. Both axes of research have been selected because of the complementarity of the dimensions of their research domains, that can position the research on ACE both at theoretical and practical levels. Figure 3 contextualise the research on ACE along the respective dimensions of the IE and LSS research domains.

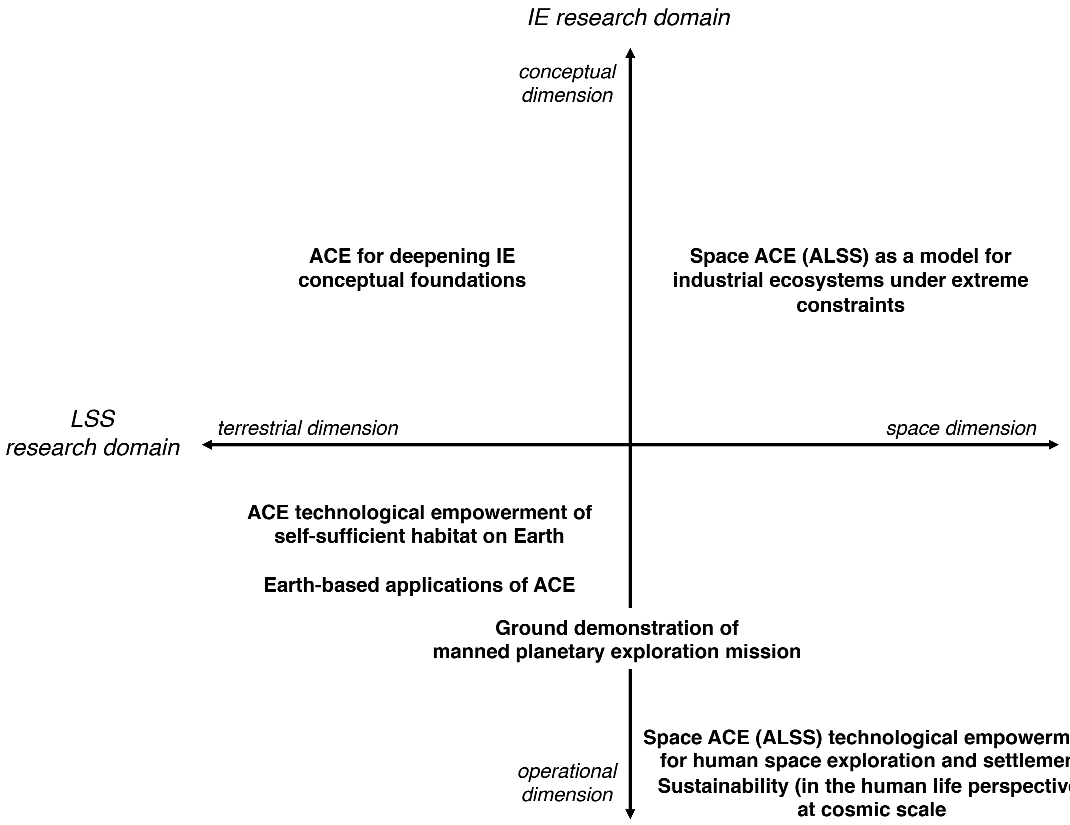

Figure 1: Contextualisation of the research on ACE along the research domains of IE and LSS.
Combining the conceptual and terrestrial dimensions underscores the role of ACE for deepening IE conceptual foundations, whereas the confluence of conceptual and space dimensions highlights how space ACE or ALSS can be considered as a model for industrial ecosystems under extreme constraints. Then, the intersection of operational and terrestrial dimensions showcases the interest of Earth-based applications of ACE and of the technological empowerment by ACE for developing self-sufficient habitat on Earth. Next, the coupling of operational and space dimensions displays the potential of space ACE (ALSS) technological empowerment for human space exploration and settlement and the notion of sustainability (in the human life perspective) at cosmic scale. Finally, ground demonstration of manned planetary exploration mission stands at the interface of terrestrial and space LSS dimensions together with the operational one of IE.

In a nutshell, the novelty of this thesis lies in combining the hybridisation between conceptual and operational dimensions of the IE research domain together with the synergistic approach of the terrestrial and space dimensions of ACE along the LSS research domain.

The overall research questions addressed in the three parts of the thesis can be stated as follows:

1. What is the relevance of ACE research to the conceptual foundations of IE?
2. How to cross-fertilise the terrestrial and space dimensions of LSS development?
3. What are the contributions of ACE development to the operationalisation of IE?

Part I: Relevance of ACE research to the conceptual foundations of IE

The first part of this PhD thesis studies the relevance of ACE research to the conceptual foundations of IE.

Chapter 2 first examines the conceptual background of this research and describes key elements from the concept of IE, starting with a brief historical perspective of the concepts of ecology and ecosystem, followed by a focus on the 'ecology' of IE. The latter section illustrates the early years of the young research field of IE, and discusses the analogy between the natural and industrial ecosystems by reviewing the waste analogy, biological and industrial organisms, biological and industrial metabolisms and considerations for energy and matter dissipation.

Chapter 3 proposes key concepts for ACE analysis in the perspective of IE. It positions ACE in the context of scientific and industrial ecology. Next, it provides essential principles of systems to better apprehend ACE by introducing the notions of system feedback and control. Later, it explores key concepts for ACE analysis in the perspective of IE and investigated their relevance for consolidating the conceptual foundations of IE. The examined concepts encompass 'interactions' on artificially predefined symbioses in circular systems, 'cycling', 'biodiversity', 'compartmentalisation', 'reproduction' and 'evolution'.

Chapter 4 reviews the key milestones of the space exploration. Subsequently, it introduces space ACE, namely space advanced life support systems (ALSS). Then, it spotlights that when operating under the radical conditions of the space context, a space ACE can be envisioned as a model for industrial ecosystems under extreme constraints. Chapter 4 considers space ACE as highly sophisticated, efficient and resource-saving quasi-circular systems whose technical operation have been optimised to the maximum extent to sustain life in extreme conditions, and which should allow ultimately for the full recycling of material flows in space habitats. It also points out that a ground simulator of such minimal case of a 'hybrid' ecosystems should be envisaged as a novel experimental platform for testing a whole series of high technologies needed not only to prepare for a 'Mars Mission', but also those likely to drastically improve the environmental performance of recycling systems. In this context, space ACE are undeniably considered as constituting a relevant experimental framework for the analysis of industrial ecosystems operating under extreme constraints.

As the reception of ACE theory in the direction of IE has been rather preliminary so far, Part I attempts to clarify the potential, relevance and interest of ACE in order to consolidate the conceptual foundations of IE. By leveraging the study of integral recycling loops in the context of an expanding society and a world of finite resources, ACE are considered as relevant tools for the maturation of industrial ecosystems. All in all, this first part demonstrates that ACE development represents an excellent compromise and has an untapped potential for developing further the theoretical basis of IE.

Part II: Cross-fertilising the terrestrial and space dimensions of LSS development

The second part of this work focuses on the possible ways to cross-fertilise the terrestrial and space dimensions of LSS development.

Chapter 5 formulates a preliminary research agenda for the Oïkosmos science and technology programme. In particular, it illustrates how a full-scale crewed ACE ground demonstrator for preparing manned planetary exploration in the most realistic closed-loop conditions would leverage and intensify the implementation of a space and terrestrial research agenda on ACE. Chapter 4 shows that Oïkosmos, as a synergistic R&D programme on ACE, comprises a mapping of a broad range of research topics for the fields of IE, systems biology, ICT and closed and sustainable habitat.

Chapter 6 assesses the ways to develop and exploit a ground demonstrator of ACE as a technological platform for the study of circular systems (RO2.2). It conceptualises the opportunities for knowledge and technology transfer it offers, and maps the multiple modalities of use, operational activities and services that such technology platform provides to the actors of the Research-Innovation-Market value chain. As the cornerstone of the Oïkosmos programme, the ACE demonstrator could have a life of its own by offering spaces for promoting innovation, science and technology: conference and seminar rooms, exhibition halls, restaurants, etc. The gradual development of additional activities and of a network of skills through a forum, a competence centre and an incubator would make the simulator's environment – already technically favourable – conducive to exchanges of technological and commercial experience and practices, making it more than a series of ultramodern infrastructures adapted to the needs of its tenants, users and clients. Chapter 6 concludes that a dynamic could thus form around the ACE demonstrator to compete for access, space, equipment and expertise around its technological platform, in the same way that physicists compete to use the few particle accelerators available, or astronomers compete for access to large-scale telescopes.

Chapter 7 presents a position paper on the 'consolidation of the Swiss activities and rationale for ALSS and MELiSSA development'. More particularly, the paper explores, maps and assesses the Swiss activities, interests and strengths in LSS, in the framework of MELiSSA roadmap. As an outcome, Chapter 7 shows evidence that the current timing appears highly adequate for consolidating the Swiss activities and rationale for ALSS into an active and productive cluster; for positioning Switzerland as a key player in space and terrestrial ALSS; as well as for allowing an increased international visibility for Switzerland in the field of manned space exploration.

Chapter 8 demonstrates the terrestrial and space research synergy potential through the elaboration and consecutive implementation of a concrete R&D project (spin-in or spin-out), with the concrete example of the BELiSSIMA project (spin-out). In particular, Chapter 8 shows how such ACE-based project could be used to observe the effects of various microcompounds (such as endocrine disruptors, biocides, etc.) and trace elements on several categories of species under test conditions that are more realistic than those of a laboratory.

Chapter 9 illustrates a possible co-development technology roadmap with an exemplifying prototyping projects series – the SUMIT projects – which presents a potential both for spin-in and spin-out pathways. It discusses the usefulness of the SUMIT urinalysis devices using miniaturised sensors, not only for the non-invasive monitoring of crew health, but also for the overall functionality of ALSS (e.g. regulation of the urine loading to a downstream nitrification process, proper nutrition of food plants, prevention of scaling in water recovery processes, etc.).

Chapter 10 then presents the proceedings of the ESA Closed Habitat Forum 2016. This event is one of the components of the stakeholder engagement strategy for consolidating the current Swiss activities and rationale for LSS and MELiSSA development into an active and productive cluster, together with the position paper, and BELiSSIMA Phase A.

Chapter 11 aims to demonstrate the opportunities offered by the hosting of an ACE ground demonstrator based in Western Switzerland for its innovation ecosystem and for the Swiss space sector. It highlights the advantages of the region's participation in the development of an ACE demonstrator, which represents a way: to strengthen Swiss institutional participation in ESA activities – which seems all the more relevant since ESA sometimes has difficulties in financing space projects carried out in Switzerland; to bring together under a single umbrella a unique panel of strategic technologies for

Switzerland, within a platform integrating interdisciplinarity upstream of its development, from the early R&D phases; to consolidate the existing dynamics between economic promotion, entrepreneurship and innovation; and to strengthen the region's position as a centre of excellence on the European eco-innovation map. It concludes that it would be desirable for Western Switzerland to develop an institutional strategy in favour of its participation in the Oïkosmos programme and to encourage the progressive setting up of an ACE demonstrator in the region.

Chapter 12 explores some of the possible ways to foster the institutional dynamics for ACE and LSS development in Switzerland and promote related education and communication activities. In particular, it proposes accompanying measures, recommendations and suggestions to the Direction of the University of Lausanne. It also presents the pedagogical concept around the teaching unit EPFL ENAC Building on Mars.

Part III: Contributions of ACE development to the operationalisation of IE

The third part of this PhD work tackles the contributions of ACE development to the operationalisation of IE.

Chapter 13 analyses the potential of ACE development for the technological empowerment of self-sufficient habitat on Earth. It introduces the context in which Earth Space Technical Ecosystem Enterprises SA (ESTEE) was created, as a continuation of the Oïkosmos Report. Next, it describes the high-level specifications of two key projects of ESTEE, namely Scorpius Prototype 1 and Scorpius Laboratory Prototype 1, that aim at establishing a proof of concept of a CH and ACE demonstrator. Furthermore, it addresses the question of the habitability optimisation of CH, by exploring the notion of human habitat and the enhancement of comfort through user-building symbiosis. Afterwards, it conceptualises CH as minimal habitats for self-sufficiency in the perspective of IE. Finally, it provides considerations on the technology empowerment from ACE development for self-sufficient habitat on Earth.

Chapter 14 compiles the contributions of ACE development to terrestrial sustainability, which flow from the ground preparation of manned planetary exploration missions and parallel development of specific ACE-based terrestrial solutions. It summarises the contributions to terrestrial sustainability identified previously. Next, it analyses the potential of ACE development for Earth-based applications, by mapping their related possible market segments based on the Oïkosmos Report and on market research and stakeholders analysis and by describing an assessment of space ALSS technologies business and financial potential for Earth-based applications (EXPRO+ study, in which ESTEE led the technical side of the assessment). Later, Chapter 14 introduces the notion of circular economy and presents a selection of contributions of ACE development to circular economy. Eventually, it provides considerations on the contributions of ACE development to terrestrial sustainability.

With the benefit of hindsight from the overall outcome of this research, Chapter 15 considers the possible ways to envisage sustainability (in the human life perspective) at cosmic scale. It introduces the emerging field of New Space. It then discusses the rise of space tourism and examines space colonisation as a necessary expansion of humanity in the solar system. Subsequently, it describes the approach of space sustainability and investigates the extension of the notion of space sustainability to cosmic scale. Finally, it considers the contributions of ACE development to space sustainability.

Timeline and mapping of research outputs and ACE-related activities

This PhD thesis manuscript gathers together diverse research outputs related to the research activities as a PhD candidate, assistant, and research fellow at the University of Lausanne since 2008, as well as co-founder and managing director of ESTEE since 2013. Figure 55 gives the chronology of research outputs and of ACE-related institutional, educational and communication activities implemented during the elaboration of this PhD work.

These research outputs have been developed through a back-and-forth process, with initially a more space-oriented centre of attention on the research agenda preparation of human space exploration in ground simulators (Oïkosmos Report), followed by the deployment of prototyping activities of such simulator as well as the development of Earth-based applications of ACE through the activities of ESTEE, which aims to develop an ACE demonstrator, namely the Scorpius Prototype 1, as well as with joint projects such as ESA's BELiSSIMA and Assessment of financial business potential of ALSS. In parallel, other projects with both space and terrestrial focal points have been pursued like Swiss Position Paper and SUMIT projects.

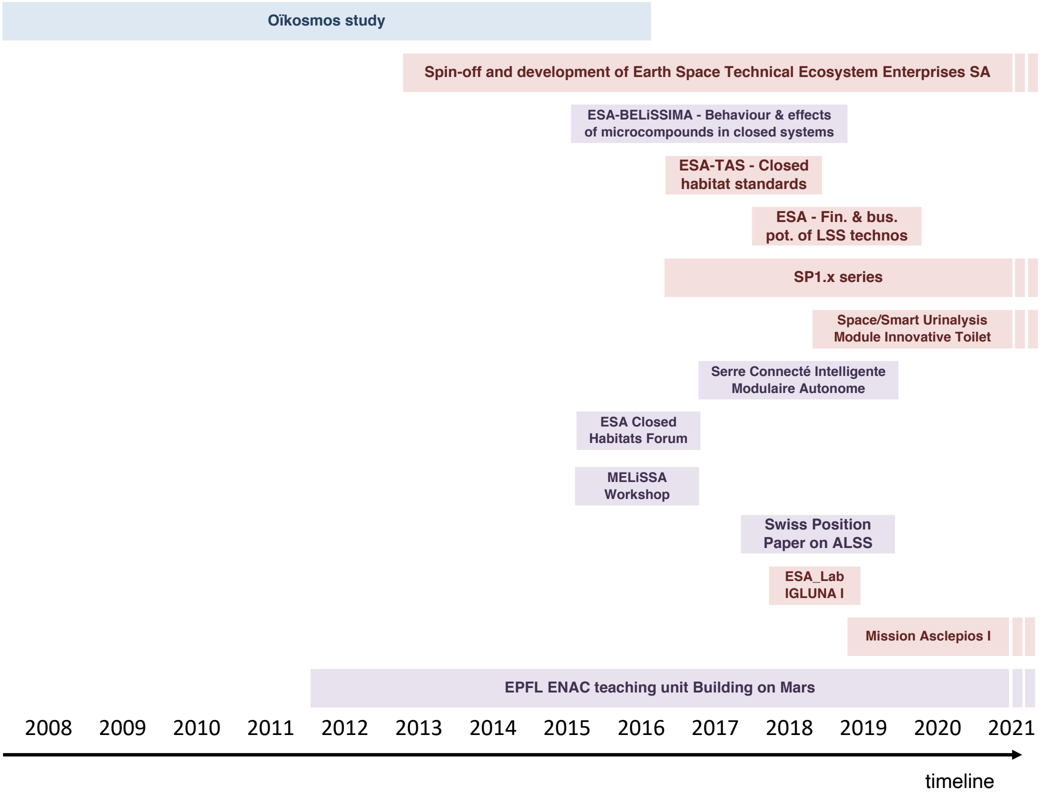

Figure 2: Chronology of research outputs and ACE-related institutional, educational and communication activities. Activities generated within the implementation of the PhD thesis are coloured depending on the organisation leading the project: Activities led by UNIL in blue, led by ESTEE and based by the activities from Oïkosmos Report in red, joint contribution of both UNIL and ESTEE is highlighted in purple.

Oïkosmos programme

Oïkosmos does not pretend to solve everything that concerns ecology. It is primarily a closed-system ecology project in which recycling is exacerbated by the narrowness of the site. But if one aspires that the study of such very significantly reduced model can truly offer advice for solving larger issues – i.e. on the scale of the whole planet – inextricably linked to terrestrial sustainability, it seems necessary to extract some of their functions in order to size them on a larger scale (case of decentralised recycling of wastewater), or to include an additional external supply (case of the contribution of CO_2 allowing to largely extend the quantity of organic molecules circulating in the system).

Oïkosmos is an audacious project that seems to be able to create a decisive momentum for the development of research on closed systems. A key challenge is to go beyond the standard vision of a specific development on space, separated from the terrestrial one, or at least implement sequentially, and to envision it rather a synergistic way, within a co-development process. Therefore, the *raison d'être* of Oïkosmos is about the fact that synergies of R&D between manned space missions and terrestrial issues can benefit both.

Furthermore, the ACE research agenda allows questions to be formulated under extreme conditions. It is therefore conceivable that the answers found could enable the development of applications that would not have been identified under normal conditions.

One of the purposes of Oïkosmos is to accelerate ACE development. Of course, the realisation of such an ambitious research programme will still require many scientific and technological advances. In the meantime, Oïkosmos could serve as a springboard for the technological development of innovative and exemplary solutions, with promising terrestrial ACE applications based on the use of a module or technology, or a combination of them. The positive spillovers of the dissemination of these new or emerging technologies from the Oïkosmos programme should contribute, at their own scale, to the resolution of pressing issues and challenges facing European society, both in terms of environmental and human health management.

ACE demonstrator

In such context, a complete European ACE demonstrator would become a place for implementing integrative science and technology developments and blurring the boundaries between space and terrestrial experimental R&D research. It would play more than ever a key role in cross-fertilising this dual scientific and technological LSS roadmaps.

With its strong connections to both space and terrestrial sustainability, it appears that ACE development should keep a down-to-Earth mindset focused on scientific exploration and Earth-based applications, to engage and federate a maximum of stakeholders and reach the widest possible audience.

Therefore, a thoughtful and balanced mix of researchers, specialists and experts collaborating at all levels of the 'Research-Innovation-Market' value chain would thus position the ACE demonstrator both as a driver of eco-innovation and as an amplifier of interactions and partnerships. In addition, it would represent a new kind of testbed and a formidable instrument for promoting the development of innovative applications and solutions. In the long term, it should become a technological showcase for 'made in Europe' applications at the convergence of space and terrestrial sectors, which would enhance credibility and shape a global and constructive opinion around ACE development.

In conclusion, an ACE demonstrator is essential to implement the space and terrestrial R&D agenda on LSS. Furthermore, such Earth-based experimental closed facility would be instrumental for further improving and developing LSS technologies as well as new methods and thinking, and particularly for engaging new stakeholders from space and terrestrial organisations, and integrating the latest technological progress made in other R&D fields.

Closed habitats

Space exploration allows us to better understand life in confinement. With its sudden imposed restricted living conditions since early 2020, the COVID-19 pandemics indirectly illustrated the immense challenge of confinement in space vehicles and the relevance of ACE subsystems wide diffusion for the benefit of citizens. More concretely, the ongoing sanitary crisis created a new stay-at-home economy for shopping, working, learning, cooking, health and entertainment. Its impacts showed the importance of LSS technologies (e.g. remote health monitoring, microbial safety, air quality management, etc.) for proactive and reactive health management (habitat environment monitoring, point-of-care diagnostic, household and personal cleaning with antiseptic liquid and sanitisers) or on-site pantry preparation in self-sufficient habitat.

Beside its strong technical and scientific requirements, an ACE demonstrator consists above all of an LSS for humans. More than a technological dependence, it provides to human a vital connection, a bubble sustaining life. Nonetheless, the final vision of a CH is not just ensuring the survival at the individual level. Rather, it aspires to link a technical approach to human, social and environmental concerns. In return, it makes it possible to revisit what is living and what is a 'home' at the level of a minimal habitat, crucial for dealing both with space and terrestrial sustainability issues.

By reconditioning to human purpose a limited set of simplified ecosystems processes and services within a liveable habitat, CH have the capacity to ensure self-sufficiency for one or a few occupants. A CH can be considered as a minimal habitat, a living unit for long-duration dwelling within a sustainable habitat, a man-made closed ecosystem for humans.

ALSS roadmap

The completed crewed closed experiments of ALSS so far are all Earth-based experiments, which differ deeply with extraterrestrial environment in terms of gravity, magnetic fields or radiations. Consequently, long-term operations of ACE must be carried out in a space context such as in a space station, on the Moon or on Mars to ensure their proper calibration and progressively established a safe crewed space ACE.

The high quality of the European scientific and engineering approach can continue to benefit from this common, multilateral, and multidisciplinary effort in leveraging further human space exploration together with the development of thriving spin-out applications, an epic journey full of businesses. In the coming decade, such continuation nonetheless implies to consolidate a clear, harmonised and robust strategy at European level (Lasseur 2020).

Even if at the moment, and possibly still for a while, standard physico-chemical LSS are the norm for space exploration with increased levels of loop closure and higher reliability, we will eventually rely on synthetic, engineered and highly controlled biospheres to provide a tasty diet based on the transformation of waste into edible food. Advanced, microbiology-based LSS will be progressively phased in, as their maturity progresses, and as they present many benefits to the crew. The purpose of this work was to highlight those advantages, that go much beyond the crew, with the terrestrial spin-off solutions of which would benefit for the citizens.

For the first time in 30 years, regenerative life support is part of ESA exploration roadmap through the Terrae Novae programme (ESA Industrial Policy Committee 2021), which is ESA's European Exploration Envelope Programme (E3P) bringing together all ESA exploration activities and missions into a single programme. ESA is not positioning itself only as a transporter but now, as well as an habitat designer and developer. This could start with the full development of a habitation module, potentially connected to ISS or CIS Lunar orbiter to demonstrate and validate the necessary LSS and health technologies for the Mars transit phase. A preliminary study is supposed to be concluded for ESA ministerial council of November 2022.

Final considerations

Humans act as a catalyst of evolution, and are now transforming their surrounding environment at all scales, as strikingly illustrated by what seems to be the unstoppable development of New Space. ACE development must embrace this technological progress and make the best out of the ongoing space industrialisation. New Space should clearly become a key driver for the next decades manned planetary exploration, and its potential to indirectly enhance space ACE development is real. In particular, with the current booming of commercial space-based start-ups and space-driven private ventures, space ALSS should gain more visibility and accelerate its development.

Nonetheless, in the light of the expansion of New Space, a distinction should especially be made between space tourism, exploitation, exploration and settlement. Even if a permanent settlement on another planet, on the Moon or in a space station requires the use of ACE, one should avoid confusing the issues of long-term space exploration missions with space industrialisation at the Solar System scale.

The next frontier for sustainability is space. Such extension of sustainability scope involves the integration of the terrestrial scale with the scale of Solar System, and even beyond. ACE encode narratives on the way space sustainability can take place and are of major importance for overcoming the pitfalls of space sustainability. By disseminating and applying the lessons learnt in closed systems, ACE promoters – such as MELiSSA partners and ESTEE – are operationalising the principles of IE, and thus enabling the effective implementation of the megatrend of sustainability at practical levels for positive societal returns.

ACE and LSS are eye-openers to gain inspiration. They open up new avenues for the control and regulation of ecosystems leading to new facets of interpreting nature and the improvement of health in general within a CH. It can be deduced from this work that the realisation of the promises of ACE development will depend on an open and constructive dialogue between medicine, biology, humanities and environmental sciences, enabled by engineering and digitalisation capacities.

All in all, space exploration is about preparing the future, in a sense that it should benefit the Earth right now, and be instrumental for the betterment of society. Therefore, human space exploration could be considered as a topic of the upmost importance simply because of the value of the Earth-based applications of space ACE technologies.

Even if manned long-duration and remote space missions would not be carried out, research for hyper-efficient space ACE is worth doing anyway not only due to the growing constraints on Earth, but to their potential for the sustainable resource management on Earth. Therefore, this research anticipates that ACE components will be developed in any case for their relevance for terrestrial sustainability, and their market applicability into everyday life.

Because of its orientation towards circularity, its eco-innovative nature, together with its broad field of application, the research on ACE and LSS has the potential to occupy a central position in the development of IE.

As evidenced by this thesis, research on ACE and LSS is an excellent instrument to forge a sustainable future, by elaborating more closed industrial ecosystems, more sustainable in the face of decreasing supplies of raw materials and increasing problems of waste and pollution. Therefore, synergies of terrestrial and space R&D on ACE and LSS can act as drivers for implementing sustainability, in the perspective of IE.

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Working in a sector related to space is fascinating and even more inspiring when it can be beneficial to terrestrial sustainability. This thesis enabled me to leverage my backgrounds in biology, environmental management, and business development, and to meet exceptional people: brilliant researchers and scientists, innovative industry and tech leaders, outstanding astronauts, visionary investors, pioneering startupers, and far-sighted policymakers. All over the years, I have been continuously overwhelmed by an avalanche of opportunities from the various key practitioners in the attractive fields of artificial closed ecosystem, life support systems and industrial ecology, which made this thesis elaboration a stimulating and astonishing journey for me.

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[4] For his contribution on microbiomics in Annex A-§8.3.3.3.

[5] For his contribution on ecosystems adaptative capacities in Annex A-§7.3.4.3.

[6] For his contribution on green chemistry in Annex A-§ 7.3.4.3.

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[10] In particular for his contributions for the development the Scorpius Prototype 1 and Scorpius Laboratory Prototype 1 in §13.2, and for the mapping of Earth-based applications of ACE in §14.2

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[11] Cf §9, as well as for his contributions on circular economy in §14.4.3 and §14.4.4, and on BELiSSIMA project in Annex C.

[12] For their contributions on exploring the notion of closed habitat, cf §13.3.1.

[13] For his contribution to BELiSSIMA project in Annex C2b.

[14] For her contribution on greenhouses for food production, in particular in Figure 33 and Figure 34.

[15] For her contribution on closed habitat specifications in Annex H, as well as in Figure 59, Figure 60 and Figure 61.

[16] For her contribution and guidance while preparing the ESA Closed Habitat Forum in Annex E.

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ABBREVIATIONS

ACE: Artificial Closed Ecosystem

ALiSSE: Advanced Life Support System Evaluator

ALSS: Advanced Life Support System

BE: Biological Ecology

BO: Biological Organism

BLSS: Bioregenerative Life Support System

CELSS: Controlled Ecological Life Support System

CH: Closed Habitat

CM: Crew Members

CP: Cleaner Production

CSEM: Centre Suisse d'Electronique et de Microtechnique

Eawag: Swiss Federal Institute of Aquatic Science and Technology

E3P: European Exploration Envelope Programme

EIP: Eco-Industrial Parks

EMPA: Swiss Federal Laboratories for Materials Science and Technology

EPFL: École Polytechnique Fédérale de Lausanne

ESTEC: European Space Research and Technology Centre

ESTEE: Earth Space Technical Ecosystem Enterprises SA

ESA: European Space Agency

EXPERT: Exploration Preparation, Research and Technology

FIPES: Facility for Integrated Planetary Exploration Simulation

FPCU: Food Processing Characterization Unit

GSTP: General Support Technology Programme

HEI: Haute École d'Ingénierie de la HES-SO//Valais-Wallis

HEIA-Fr: Haute École d’Ingénierie et d’Architecture de Fribourg

HMI: Human-Machine Interface

HPA: High Pressure Aeroponics

HSLU: Hochschule Luzern

ICT: Information and Communication Technologies

IE: Industrial Ecology

ILS: Illumination Lighting System

IO: Industrial Organism

ISRU: In-Situ Resource Utilisation

ISS: International Space Station

LCA: Life Cycle Analysis

LSS: Life Support System

MBR: Membrane Bioreactor

MELiSSA: Micro-Ecological Life Support System Alternative

MEMS: MicroElectroMechanical Systems

MFA: Material Flow Analysis

mHealth: Mobile Health

MPP: MELiSSA Pilot Plant

MRL: Market Readiness Level

NASA: National Aeronautics and Space Administration

NDS: Nutrient Delivery System

NICT: New Information and Communication Technologies

OMICs: Omic sciences (genomic, proteomic, metabolomic, microbiomic, etc.)

P&ID: Piping and Instrumentation Diagram

POMP: Pool of MELiSSA PhD

PPP: Public-Private Partnership

PSI: Paul Scherrer Institute

RO: Research Objective

RQ: Research Question

SciSpace: Science in Space Environment

SE: Scientific Ecology

SME: Small and Medium Enterprise

SP1: Scorpius Prototype 1

SSC: Swiss Space Center

SSO: Swiss Space Office

STEM disciplines: Science, Technology, Engineering, and Mathematics disciplines

SUMIT: Space/Smart Urinalysis Module For Innovative Toilet

TRL: Technology Readiness Level

UEE: Unité d’enseignement ENAC; ENAC Teaching Unit

UNIL: Université de Lausanne

USP: Unique Selling Proposition

WAO: Wet Air Oxidation

WMS: Waste Management System

KEYWORDS

artificial closed ecosystems; life support systems; advanced life support systems; industrial ecology; industrial ecosystems; sustainability.

synergies of terrestrial and space R&D; interdisciplinarity; ground demonstration; technology platform; co-development; technological trajectories; technology transfer.

bio-inspiration; scientific ecology; industrial metabolism; industrial symbiosis; systems biology; biomonitoring.

integral recycling; waste valorisation; resource recovery; nutrient recovery, sustainable resource management.

closed habitat; self-sufficient habitat; closed systems; circular systems.

Earth-based applications; terrestrial applications; eco-innovation; circular economy.

New space; space habitat; human space exploration; space industrialisation; space colonisation; space sustainability.

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INTRODUCTION

In its introductory part, Chapter §1 first exposes the context of the PhD thesis and its research framework (§1.1). Subsequently, it presents the research questions (§1.2) and their respective research objectives, activities and outputs (§1.3.1-§1.3.3). Eventually, it shows PhD thesis structuration (§1.3.4).

1 Context, research questions and methodology

1.1 Context of the PhD thesis and research framework

The present work fits within the context of the following major trends:

- The development of the field of industrial ecology, in the broader context of research and development in the area of sustainability (including circular economy, cleaner production, sustainable consumption, etc.);
- The development of habitats demonstrating high levels of material closure and self-sufficiency (tiny house, off-grid habitat, autarkic habitat, etc.), as well as featuring proper conditions for a healthy habitat (telework; telehealth, especially for elderly people), in particular with the COVID-19 sanitary crisis of 2020-2021 and its wide implications in terms of biosafety;
- The growing production of organic and locally sourced food with high nutritional value and the advancement of agriculture in confined space (including vertical/urban farming or 3D-agriculture);
- The development of eco-innovation (or responsible innovation), including new business models (product service systems, mHealth, etc.);
- The advancement of life support systems for space purposes, and their associated Earth-based applications, in the context of the emergence of New Space;
- The recent and spectacular development of the disciplinary fields of systems biology and 'omics' sciences (including metabolomics, microbiomics and nutrigenomics);
- The ubiquitous trend of digitalisation, in particular in relation to the fields of information and communication technologies (but also Industry 4.0, smart cities, etc.), artificial intelligence, (Big) Data management and e-Health.

Until recently, the above-listed trends and themes were characterised by their different origins, distinct evolutions and own development trajectories. One of the objectives of this thesis is to show how they built on increasing convergences.

Among such a wealth of topics, this thesis focuses more specifically on the convergence of two main research domains – industrial ecology (IE) and life support systems (LSS) –, a convergence that will be further examined in the context of development of closed systems, namely 'artificial closed ecosystems' (ACEs). The choice of studying ACE along the axes of IE and LSS research domains is based on the strong convergence of their development trajectories since the late 1990s/early 2000s. On one hand, this work analyses ACE in the perspective of the domain of IE, and, on the other hand, in the perspective of the experimental framework of LSS, which constitute the two main axes of this research. Both axes of research have been selected because of the complementarity of the dimensions of their research domains, that can position the research on ACE both at theoretical and practical levels. Figure 3 contextualise the research on ACE along the respective dimensions of the IE and LSS research domains.

For the research domain 'industrial ecology', a first dimension concentrates on the theoretical aspects of IE and explores how the analysis of ACE can foster and consolidate the conceptual foundations of the field of IE. Through the conceptual background of IE, this thesis addresses both industrial and scientific ecology and particularly aims at deepening industrial and natural ecosystems analogies in the context of ACE analysis. A second research dimension emphasises on the operationalisation and implementation processes of ACE in the perspective of IE, with various associated case studies as research outputs and spin-off projects.

For the research domain 'life support system', a first dimension focuses on the use of LSS for space exploration purposes – namely Advanced LSS or ALSS – and more particularly on how to simplify and miniaturise ACE in order to envision long-duration missions for possible human settlements in the Solar System, and possibly beyond, thus radically expanding the notion of sustainability (in the human life perspective) at cosmic scale. The second research dimension is connected to the exploitation of circular systems for terrestrial purposes, either as a whole in a self-sufficient habitat or through the possible uses of the components and technological solutions of ACE for various kinds of Earth-based applications. Finally, ground demonstration of manned planetary exploration mission stands at the intersection of terrestrial and space LSS dimensions.

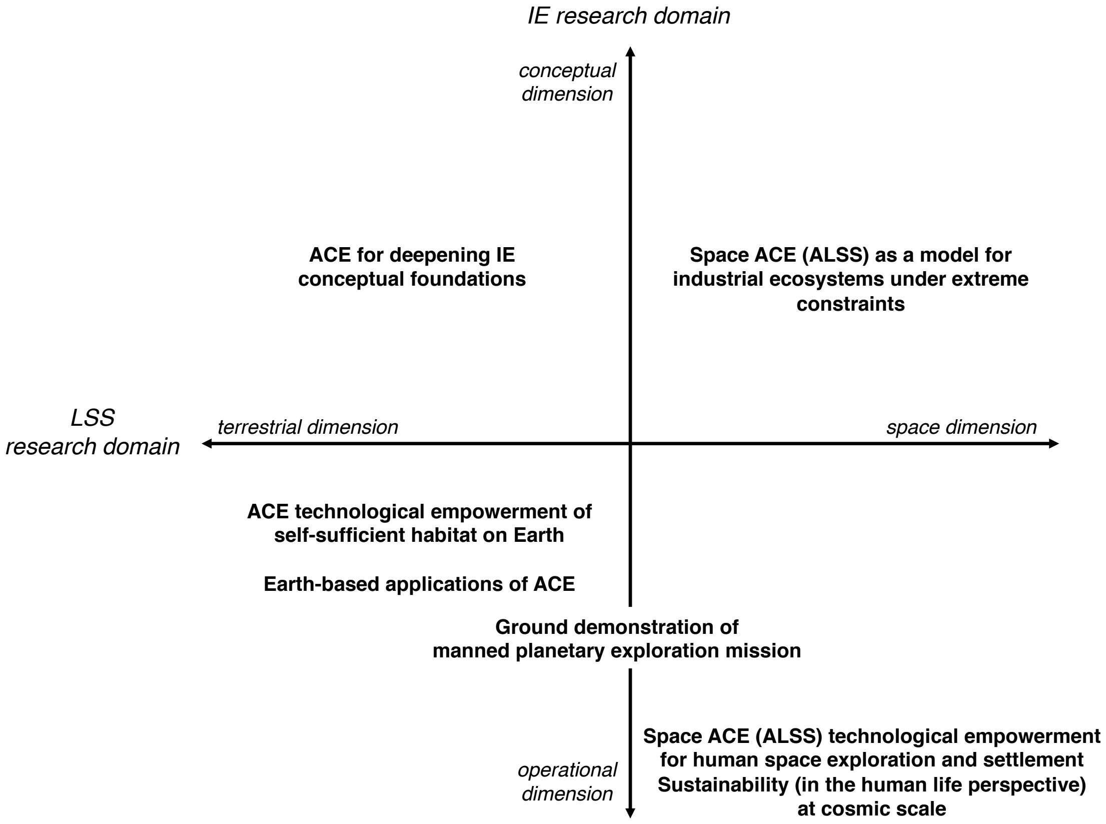

Figure 3: Contextualisation of the research on ACE along the IE and LSS research domains.
Combining the conceptual and terrestrial dimensions underscores the role of ACE for deepening IE conceptual foundations, whereas the confluence of conceptual and space dimensions highlights how space ACE or ALSS can be considered as a model for industrial ecosystems under extreme constraints. Then, the intersection of operational and terrestrial dimensions showcases the interest, on the one side, of Earth-based applications of ACE and, on the other side, of the technological empowerment by ACE for developing self-sufficient habitat on Earth. Next, the coupling of operational and space dimensions displays the potential of space ACE (ALSS) technological empowerment for human space exploration and settlement and the notion of sustainability (in the human life perspective) at cosmic scale. Finally, ground demonstration of manned planetary exploration mission stands at the interface of terrestrial and space LSS dimensions together with the operational one of IE.

In a nutshell, a first original facet of this work comes from the hybridisation, on the one hand, from the conceptual and operational dimensions of the IE domain and, on the other hand, from the integration of the theoretical and experimental aspects of ACE research. In other words, the approach for apprehending ACE reflects a dual dimension of the field of study and action of IE for the analysis and the transformation of the industrial system. Moreover, another specificity of this thesis is illustrated by its synergistic approach for the study of terrestrial and space orientations of ACE along the LSS axis. By combining the hybridisation process and the synergistic approach, the present research aims at enhancing the complementarities of the dimensions of IE and LSS at the interfaces of the respective research axes.

1.2 Research questions

The three overall research questions (RQ) can be stated as follows:

- What is the relevance of ACE research to the conceptual foundations of IE? (RQ1);
- How to cross-fertilise the terrestrial and space dimensions of LSS development? (RQ2);
- What are the contributions of ACE development to the operationalisation of IE? (RQ3).

As argued above, the novelty of this thesis lies in combining the hybridisation between conceptual and operational dimensions of the IE research domain together with the synergistic approach of the terrestrial and space dimensions of ACE along the LSS research domain.

The next section describes the research methodology followed to answer to the above research questions, and provides their related research objectives, as well as the activities implemented to reach these objectives. In addition, it mentions research outputs elaborated during the progession of this thesis.

1.3 Research objectives, activities and outputs

1.3.1 RQ1: What is the relevance of ACE research to the conceptual foundations of IE?

The first part of this PhD thesis studies the relevance of ACE research to the conceptual foundations of IE (RQ1).

The research objectives (RO) related to RQ1 are as follows:

- to review the analogy between the natural and industrial ecosystems (RO1.1);
- to propose key concepts for ACE analysis in the perspective of IE and investigate their relevance for consolidating the conceptual foundations of IE (RO1.2);
- to examine space ACE (ALSS) as models for industrial ecosystems under extreme constraints (RO1.3).

Research activities for covering RO1.1, RO1.2 and RO1.3 consist mainly of literature review, online research as well as targeted interviews with members of the IE and ACE communities.

In preamble, Chapter 2 examines the conceptual background of this research. Initially, it describes key elements from IE (§2), starting with a brief historical overview of the ecology and ecosystem concepts (§2.1), followed by a focus on the 'ecology' of IE (§2.2). The latter section illustrates the first years of the emerging research field of IE (§2.2.1). Later, it discusses the analogy between the natural and industrial ecosystems (§2.2.2, RO1.1), notably by reviewing the waste analogy, biological and industrial organisms, biological and industrial metabolisms and considerations for energy and matter dissipation. Finally, it gives final comments on RO1.1 (§2.2.2.5).

Subsequently, Chapter 3 proposes key concepts for ACE analysis in the perspective of IE (RO1.2). It first positions the research on ACE in the perspective of IE (§3.1). Next, it provides essential principles of systems for better apprehending ACE (§3.2) by introducing the notions of system feedback and control. Later, sections §3.3 to §3.9 explore key concepts for ACE analysis in the perspective of IE and investigate their relevance for consolidating the conceptual foundations of IE (RO1.2). The examined concepts encompass: 'interactions', on artificially predefined symbioses in circular systems (§3.3); 'cycling', envisaging loop closure as rarely found in most industrial ecosystems but as a critical requirement for ACE (§3.4); 'biodiversity', for compensating ACE limited diversity by a permanent monitoring, together with a fine regulation and control of its health and environmental conditions (§3.5); 'compartmentalisation', consisting in a human-driven modular distribution of ACE organisms (§3.6); 'reproduction', as a biological process not necessarily occurring for all ACE organisms (§3.7); and 'evolution', revisiting natural evolutionary principles in the prospect of ACE (§3.8) by discussing ecosystems circularisation, ecological successions, as well as resilience, adaptive capacity and selection pressure applied to ACE. Furthermore, it provides final considerations on RO1.2 (§3.9).

Afterwards, Chapter 4 first reviews the key milestones of the space exploration (§4.1). Subsequently, it introduces space ACE, namely space advanced life support systems (ALSS) (§4.2). Finally, it examines space ACE as a model for industrial ecosystems under extreme constraints (§4.3, RO1.3).

1.3.2 RQ2: How to cross-fertilise the terrestrial and space dimensions of LSS development?

The second part of this work focuses on the possible ways to cross-fertilise the terrestrial and space dimensions of LSS development (RQ2).

The research objectives (RO) related to RQ2 are as follows:

- to formulate a research agenda for the Oïkosmos science and technology programme dedicated to the establishment of space and terrestrial research synergies on ACE (RO2.1);
- to assess how to develop and exploit a ground demonstrator of ACE as a technological platform for the study of circular systems (RO2.2);
- to explore, map and assess Swiss activities, interests and strengths in LSS (RO2.3);
- to demonstrate the terrestrial and space research synergy potential through the elaboration and consecutive implementation of a concrete R&D project (spin-in or spin-out) (RO2.4);
- to illustrate a possible co-development technology roadmap for LSS development with an exemplifying prototyping project (spin-in or spin-out) (RO2.5);
- to elaborate stakeholder engagement strategies for consolidating the current LSS and MELiSSA development (RO2.6);
- to expose the opportunities offered by the hosting an ACE demonstrator in Western Switzerland for its innovation ecosystem and for the Swiss space sector (RO2.7);
- to foster the institutional dynamics for ACE and LSS development in Switzerland and promote related education and communication activities (RO2.8).

Research activities for covering the objectives of RQ2 are notably carried out within one of the core research outputs of this work, namely the Oïkosmos Report (Annex A). This technical study, commissioned by the Direction of UNIL, has been elaborated by the author of the present monograph under the supervision of Prof. Suren Erkman, Head of Industrial Ecology Group (Besson & Erkman 2016). In brief, Oïkosmos programme studies the convergence of terrestrial and space research agendas on ACE in the perspective of IE. Oïkosmos Report is composed of five parts:

- Part I: Introduction, methodology and context of the report (Annex A-§1 to §4);
- Part II: Oïkosmos programme - Terrestrial and space research synergies on ACE (RO2.1; Research output summary in §5; Annex A-§5 to §11);
- Part III: ACE ground demonstrator: a leading technological platform for the study of circular systems (RO2.2; Research output summary in §6; Annex A-§12 to §19);
- Part IV: Towards an ACE ground demonstrator in Western Switzerland? (RO2.7; Research output summary in §11; Annex A-§20 to §22);
- Part V: Accompanying measures, recommendations and conclusions (RO2.8.a; Research output summary in §12.1; Annex A-§23 to §25).

In order to formulate a preliminary research agenda for the Oïkosmos science and technology programme (RO2.1), the following activities are carried out in Oïkosmos Report ’s Part II (Annex A-§5-11):

- Identification of the preliminary scope of the report;
- Mapping of research domains for the establishment of research synergies in Western Switzerland;
- Consolidation of the scope of the report;
- Formulation of a research agenda for the Oïkosmos programme.

Subsequently, the formulated research agenda is first contextualised with current terrestrial challenges (Annex A-§6) and then extensively detailed within four key research domains illustrating potential terrestrial and space research synergies on ACE based on ESA/MELiSSA LSS development roadmap, respectively as follows:

- Industrial ecology (Annex A-§7);
- Systems biology (Annex A-§8);
- Information and communication technologies (Annex A-§9);
- Closed and sustainable habitat (Annex A-§10);
- Final considerations (Annex A-§11);

The research output summary of Oïkosmos Report Part II is given in Chapter §5.

For the purpose of assessing how to develop and exploit a ground demonstrator of ACE as a leading technological platform for the study of circular systems (RO2.2), Part III of Oïkosmos Report (Annex A-§12 to §20) conceptualises the opportunities for knowledge and technology transfer it offers. In addition, the latter section maps the multiple modalities of use, operational activities and services that such technology platform provides to the actors of the Research-Innovation-Market value chain.

The research output summary of Oïkosmos Report Part III is given in Chapter §6.

A position paper on the 'consolidation of the Swiss activities and rationale for ALSS and MELiSSA development' (Besson & Erkman 2019), supported by UNIL rectorate, EPFL presidency and ESTEE and submitted to the Swiss Space Office, constitutes another research output on this dissertation (Executive summary in §7.1, full report in Annex B1). In order to explore, map and assess Swiss activities, interests and strengths in LSS (RO2.3), the report aims:

- to introduce the MELiSSA project and its connection with Swiss organisations (Annex B1-§1.3);
- to map the space and terrestrial LSS and MELiSSA-related activities implemented in Switzerland (Annex B1-§1.4 and §2.1);
- to assess the strengths of Swiss organisations in the context of LSS development and on the ongoing MELiSSA project (Annex B1-§2.1);
- to explore the areas of interests for possible future collaboration opportunities in the field of LSS (Annex B1-§2.1).

In order to demonstrate the terrestrial and space research synergy potential through the elaboration and consecutive implementation of a concrete R&D project (spin-in or spin-out) (RO2.4), this work encompasses the BELiSSIMA project (spin-out) (see §8 and Annex C1-C3 for sections of the technical notes written in the context of this PhD study).

With the aim to illustrate a possible co-development technology roadmap with an exemplifying prototyping project (spin-in or spin-out) (RO2.5), this work encloses the SUMIT projects (§9 and Annex D).

To elaborate a stakeholder engagement strategy for consolidating the current Swiss activities and rationale for LSS and MELiSSA development into an active and productive cluster (RO2.6), this thesis encompasses activities that aim at 1) widening the base of the existing diverse community (academia and industry) by bringing in new actors traditionally not yet involved in the ACE/LSS research, and 2) preparing the ground for a stakeholder engagement strategy in the field of ACE/LSS as an input for establishing a long-term view of Life Support technologies to be developed in Europe. The related research outcomes are: Position Paper - Consolidating the Swiss activities and rationale for ALSS and MELiSSA development (RO2.6.a (as well as RO2.3 and RO2.8.b); Executive summary in §7.1; Annex B1), BELiSSIMA Phase A (RO2.6.b (as well as RO2.4); short project description in §8.1; and more particularly its technical note TN.118.1.6 (Annex C2b), and the proceedings of the ESA Closed Habitat Forum 2016 (RO2.6.c (as well as RO2.8.c and RO3.2); short project description in §10.1).

In connection with RO2.6, Part IV of Oïkosmos Report 'Towards an ACE ground demonstrator in Western Switzerland?' (§11; Annex A-§20-§22) aims to demonstrate the opportunities offered by the hosting of an ACE ground demonstrator in Western Switzerland for its innovation ecosystem and for the Swiss space sector (RO2.7).

To foster the institutional dynamics for ACE and LSS development in Switzerland and promote related education and communication activities (RO2.8), this work initiates the following activities:

- Proposition of accompanying measures, recommendations and suggestions to the Direction of the University of Lausanne (RO2.8.a; §12.1; Annex A-§23 and §24 in Oïkosmos Report Part V);
- Elaboration of the Position Paper - Consolidating the Swiss activities and rationale for ALSS and MELiSSA development (RO2.8.b (as well as RO2.3 and RO2.6.a); Executive summary in §7.1; Annex B1);
- Organisation of ESA Closed Habitat Forum 2016 (RO2.8.c (as well as RO2.6.c and RO3.2); short project description in §10.1) and MELiSSA Workshop 2016 (RO2.8.c; Oïkosmos talk in Annex F1b);
- Lecture, teaching and co-organisation of EPFL ENAC 'Building on Mars' teaching unit (since 2012) (RO2.8.d; pedagogical concept in §12.3; article published in Proceedings of the International Conference Structures and Architecture 2013 (Annex F2b);
- Participation in conferences and seminars as a speaker for various academic, public and specialist audience (RO2.8.e; see list of given talks in Annex K, e.g. MELiSSA 25th anniversary 2014, New Worlds conference 2017, European Mars Convention 2018 (EMC18), MELiSSA conference 2020;
- As well as two main mentorship activities (§12.3):
    - ESA_Lab IGLUNA pilot project I (2018-2019) – Mentorship for an interuniversity demonstrator project (Annex F3);
    - Mission Asclepios 2020-2021 – Mentorship for project proposal for a student space mission analogue made for educational purposes based at EPFL (Annex F4).

1.3.3 RQ3: What are the contributions of ACE development to the operationalisation of IE?

The third part of this PhD work tackles the contributions of ACE development to the operationalisation of IE (RQ3).

The research objectives related to RQ3 are as follows:

- to analyse the potential of ACE development for the technological empowerment of self-sufficient habitat on Earth (RO3.1);
- to determine the contributions of ACE development to terrestrial sustainability (RO3.2);
- to investigate the possible ways to envisage sustainability (in the human life perspective) at the cosmic scale (RO3.3).

To tackle the operationalisation of IE, this dissertation deploys the following research activities to cover the objectives of RQ3:

First, to analyse the potential of ACE development for the technological empowerment of self-sufficient habitat on Earth (RO3.1; §13), this monograph: 1) introduces the context in which Earth Space Technical Ecosystem Enterprises SA (ESTEE) was created, as a continuation of the Oïkosmos Report (§13.1); 2) describes the high-level specifications of two key projects of ESTEE, namely Scorpius Prototype 1 and Scorpius Laboratory Prototype 1 (§13.2), that aims at establishing a proof of concept of a closed habitat (CH) and ACE demonstrator; 3) addresses the question of the habitability optimisation of CH, by exploring the notion of human habitat and the enhancement of comfort through user-building symbiosis (§13.3); 4) conceptualises CH as minimal habitat for self-sufficiency in the perspective of IE (§13.4); and 5) provides final considerations on the technology empowerment from ACE development for self-sufficient habitat on Earth (§13.5).

Then, this thesis discusses the contributions of ACE development to terrestrial sustainability (RO3.2), which flow from the ground preparation of manned planetary exploration mission and parallel development of specific ACE-based terrestrial solutions. It first summarises the contributions to terrestrial sustainability identified previously (§14.1). Next, it analyses the potential of ACE development for Earth-based applications (§14.2). It then introduces the notion of circular economy (§14.3) and presents a selection of contributions of ACE development to circular economy (§14.4). Eventually, it provides final considerations on the contributions of ACE development to terrestrial sustainability (§14.5).

Afterwards, with the benefit of hindsight from the overall outcome of this research, this thesis investigates the possible ways to envisage sustainability (in the human life perspective) at cosmic scale (RO3.3; §15). It first introduces the emerging field of New Space (§15.1). It then discusses the rise of space tourism (§15.2) and examines space colonisation as a necessary expansion of humanity in the solar system (§15.3). Furthermore, it describes the approach of space sustainability (§15.4). Subsequently, it investigates the extension of the notion of space sustainability to cosmic scale (§15.5). Finally, it considers the contributions of ACE development to space sustainability (§15.6).

1.3.4 PhD thesis structure

Figure 4 shows thesis structure with associated parts, chapters, research questions and objectives.

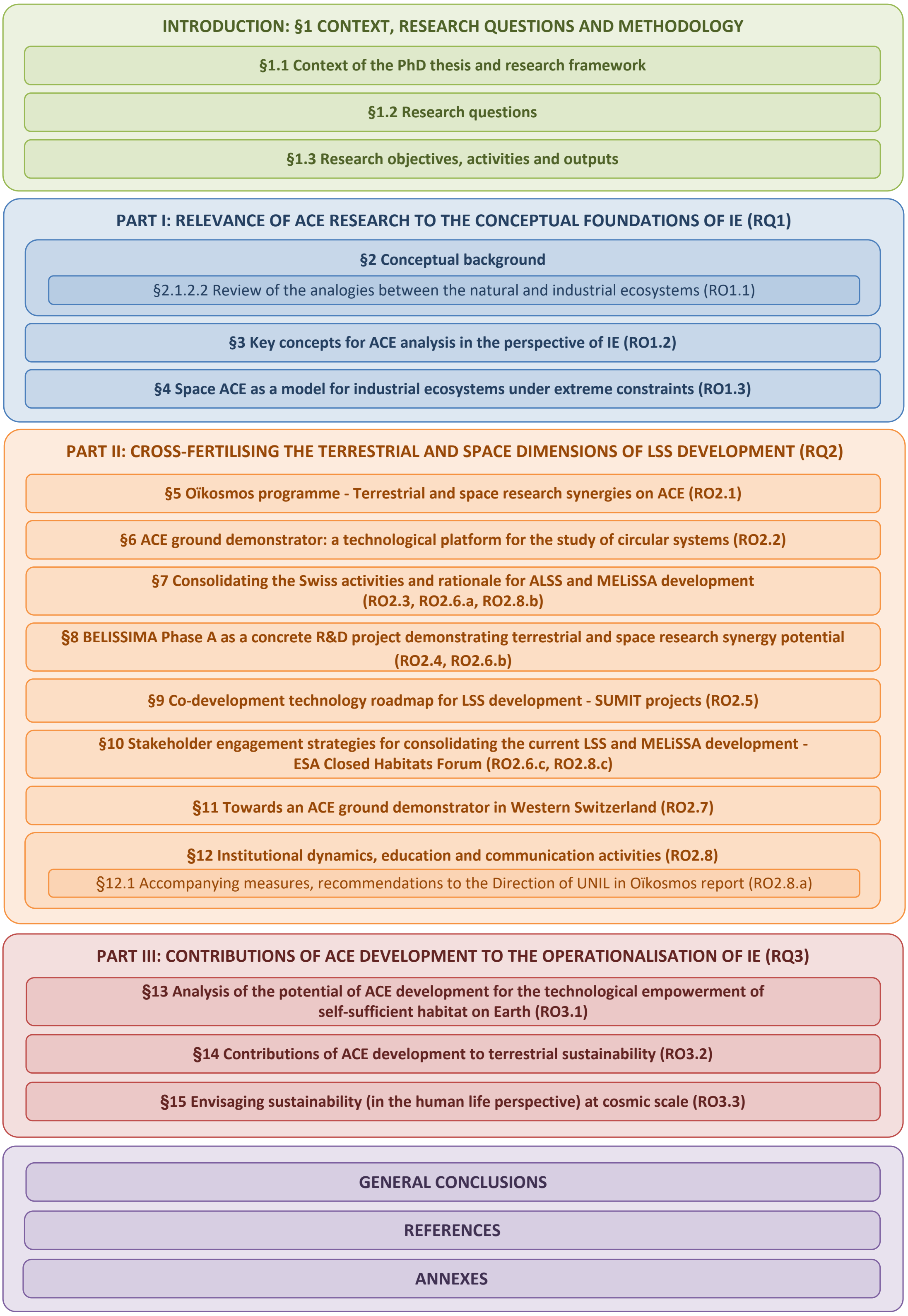

Figure 4: Thesis structuration.
Part I to III cover research questions RQ1 to RQ3. First level chapters of each part is associated to one (and sometimes several) research objectives (RO), respectively: Part I (RQ1; §2-§4): RO1.1-RO1.3; Part II (RQ2; §5-§12): RO2.1-RO2.8; Part III (RQ3; §13-§15) RO3.1-RO3.3.

PART I: RELEVANCE OF THE RESEARCH ON ARTIFICIAL CLOSED ECOSYSTEM TO THE CONCEPTUAL FOUNDATIONS OF INDUSTRIAL ECOLOGY (RQ1)

The first part of this PhD thesis studies the relevance of ACE research to the conceptual foundations of IE (RQ1).

Chapter 2 first examines the conceptual background of this research and describes key elements from the concept of IE, starting with a brief historical perspective of the concepts of ecology and ecosystem (§2.1), followed by a focus on the 'ecology' of IE (§2.2). The latter section illustrates the early years of the young research field of IE, and discusses the analogy between the natural and industrial ecosystems (RO1.1) by reviewing the waste analogy, biological and industrial organisms, biological and industrial metabolisms and considerations for energy and matter dissipation.

Chapter 3 proposes key concepts for ACE analysis in the perspective of IE (RO1.2). It positions ACE in the context of scientific and industrial ecology (§3.1). Next, it provides essential principles of systems to better apprehend ACE by introducing the notions of system feedback and control (§3.2). Later, it explores key concepts for ACE analysis in the perspective of IE and investigated their relevance for consolidating the conceptual foundations of IE (RO1.2). The examined concepts encompass 'interactions' on artificially predefined symbioses in circular systems, 'cycling', 'biodiversity', 'compartmentalisation', 'reproduction' and 'evolution' (§3.3 to §3.8).

Chapter 4 reviews the key milestones of the space exploration (§4.1). Subsequently, it introduces space ACE, namely space advanced life support systems (ALSS) (§4.2). Then, it spotlights that when operating under the radical conditions of the space context, a space ACE can be envisioned as a model for industrial ecosystems under extreme constraints (§4.3, RO1.3). Chapter 4 considers space ACE as highly sophisticated, efficient and resource-saving quasi-circular systems whose technical operation have been optimised to the maximum extent to sustain life in extreme conditions, and which should allow ultimately for the full recycling of material flows in space habitats. It also points out that a ground simulator of such minimal case of a 'hybrid' ecosystems should be envisaged as a novel experimental platform for testing a whole series of high technologies needed not only to prepare for a 'Mars Mission', but also those likely to drastically improve the environmental performance of recycling systems. In this context, space ACE are undeniably considered as constituting a relevant experimental framework for the analysis of industrial ecosystems operating under extreme constraints.

As the reception of ACE theory in the direction of IE has been rather preliminary so far, Part I attempts to clarify the potential, relevance and interest of ACE in order to consolidate the conceptual foundations of IE. By leveraging the study of integral recycling loops in the context of an expanding society and a world of finite resources, ACE are considered as relevant tools for the maturation of industrial ecosystems. All in all, this first part demonstrates that ACE development represents an excellent compromise and has an untapped potential for developing further the theoretical basis of IE.

2 Conceptual background - Key elements from the concept of IE (RO1.1)

Chapter 2 examines the conceptual background of this research and describes key elements from the concept of IE, starting with a brief historical perspective of the concepts of ecology and ecosystem (§2.1), followed by a focus on the 'ecology' of IE (§2.2). The latter section illustrates the early years of the young research field of IE and discusses the analogy between the natural and industrial ecosystems (RO1.1), notably by reviewing the waste analogy, biological and industrial organisms, biological and industrial metabolisms and considerations for energy and matter dissipation.

2.1 A brief historical overview for the notions of ecology and ecosystem

The history of the notion of 'ecology', as an academic discipline, is about 150 years old. In 1866, Ernst Haeckel coined the term 'Oekologie', from Greek 'oikos' (household). He claimed that the groundwork of ecology had been formed by Charles Darwin, with his new theory of evolution through natural selection (McIntosh 1985). Interestingly, the Oxford dictionary definition of ecology (1873) describes it as the science of economy of animals and plants. From a historical point of view, modern ecology is based on two concepts as follows: organisms are not arranged at random but, on the contrary, naturally organise themselves into distinct associations (animal or vegetal) or communities, whose structure and function cannot be understood by examining their parts in isolation from each other (Goldsmith 1988). Organisms are directly and indirectly related by trophic relations (e.g. predator-prey interaction vs trophic cascade or keystone predation benefiting at least from the second step of a trophic cascade) in interactive functional units (Moon et al. 2010). Both Clements and Shelford, two of the most distinguished of the early ecologists in the USA, defined ecology as the 'science of communities' (Clements & Shelford 1930). The Clements school (Clements 1916; Clements 1936) proposed the notions of 'superorganism' or climax community[17].

In the 1930s, the Oxford ecologist Arthur Tansley coined the term 'ecosystem' which he defined as a community taken together with its abiotic environment as follows: 'the more fundamental conception is the whole system (in the sense of physics) including not only the organism complex, but also the whole complex of physical factors forming what we call the environment. We cannot separate them (the organisms) from their special environment with which they form one physical system. It is the systems so formed which are the basis units of nature on the face of earth. These ecosystems, as we may call them, are of the most various kinds and sizes' (Tansley 1935). He defended the idea of ecosystems as functional units, born of interactions between organisms and physical factors. The ecosystem limits are usually only mental creations that facilitate their study and comparison. Man is often part of these systems.

Some early ecologists envisaged ecology as an all-embracing super-science. Barrington Moore, described ecology as 'the science of synthesis', and as being 'superimposed on the other sciences' (Goldsmith 1988). J. H. Woodger clearly saw that nature was one and that its functioning could not be understood in terms of a set of separate compartmentalised disciplines (Woodger 1929) and thus would necessarily be interdisciplinary.

The hydrological cycle, the carbon cycle, and the nitrogen cycle are familiar concepts to earth scientists. Biogeochemistry focuses on several fundamental ecosystem processes such as biologically mediated chemical cycling of nutrients and physical-biological cycling of water (Cole 2013; Leong et al. 2021). The biosphere was not always a stable system of closed cycles. Evidently, biological evolution responded to inherently unstable situations notably due to its initial open cycles by its inventiveness for developing new processes (organisms) to stabilise the system by closing the cycles through bioprocesses such as fermentation, photosynthesis, nitrification and denitrification. This self-organising capability is the essence of what has been called 'Gaia'. James Lovelock suggested that the biosphere itself could be considered a superorganism, and therefore proposed the 'Gaia' theory (Lovelock 1972). He saw 'Gaia', the overall ecosystem into which nature is organized, as the biosphere taken together with its abiotic surrounding environment, forming a synergistic and self-regulating system capable of maintaining and perpetuating the conditions for life on Earth. Ecology, seen in this light, would be indistinguishable from Lovelock's 'geophysiology' (Lovelock 1979). Moreover, according to Lynn Margulis (Margulis 1999): '*Our planetary environment is homoeostatic. […] Planetary life is highly resilient. Gaia itself is not an organism directly selected among many. It is an emergent property or*

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[17] Cf §3.8.1.

interaction among organisms, the spherical planet on which they reside, and the energy source, the sun. […] Earth as Gaian regulatory physiology transcends all individual organisms. […] Gaia is the largest ecosystem on Earth. Unlike any of its component ecosystems, Gaia is the genius of recycling.'

Eugene Odum, one of the few remaining 'holistic' ecologists defined ecology as 'the structure and function of nature' (Odum 1971), and even as 'the structure and function of Gaia'. Odum adds that besides energy flows and material cycles, ecosystems are rich in information networks comprising physical and chemical communication flows that connect all parts and steer or regulate the system as a whole. Accordingly, ecosystems can be considered cybernetic in nature, but control functions are internal and diffuse rather than external and specified as in human-engineered cybernetics devices.[18] Odum had previously defined ecosystem (1953) as a natural unit that includes living and non-living parts interacting to produce a stable system in which the exchange of materials between the living and non-living parts follows circular paths.

More recently, the concept of organisation levels has been integrated (Odum 1971). The system of functional units describes the partial systems fit into superior organisational units systems with structural and functional emerging properties, thus ensuring a certain stability (homoeostasis) within communities.

A community is a biological entity comprising a set of species populations living in a given place, with given environmental conditions, at a given time, and which have a spatial and temporal organisation, as well as functional and structuring interactions. It is independent of the scale, but at each scale, as part of the ecosystem, there are different emerging properties (Buttler 2007). Communities are characterised by unique properties (Frontier et al. 2008): structures, specific composition (species type), species distribution (spatial arrangement of textural elements to form the structure, homogeneity), species abundance (specific richness and diversity, recovery and dominance, density, biomass), trophic relations, functions, production and energy flows, resilience, and internal dynamics.

These properties of ecology are completed by scale and spatial position that characterises all ecosystems and conditions processes and exchange (landscape ecology). The landscape approach has brought nuances to the concept of ecosystem and community, such as climax patterns (Whittaker 1953). Communities can be repeated in the landscape, as fragments of a mosaic, where the combination of environmental factors remains the same (for the Clements school). But there are often atypical environments, particularly at unit interfaces. These interfaces are described as transitions or ecotones, complex and organized environments, with own properties (e.g. great diversity).

Remarkable properties of human ecosystems include cognitive and behavioral abilities, superimposition of technostructure onto biostructure, as well as new kinds of material, energy, and information flows and sinks (Stepp et al. 2003).

The above-described notions of scientific ecology and ecosystems will be further discussed in the next chapters in order to develop relevant concepts for examining artificial closed ecosystem in the perspective of industrial ecology. Industrial ecology, which constitutes the core approach of this research both at analytical and operational levels, is first introduced hereafter.

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[18] Cybernetics is the interdisciplinary study of the structure of complex systems, especially communication processes, control mechanisms and feedback principles. Cybernetics is closely related to control theory and systems theory (see systemics principle in §3.2).

2.2 The ‘ecology’ of industrial ecology[19]

2.2.1 Industrial ecology: the first years of an emerging research field

Humans have progressively been ‘pushing biological limits’ since the industrialisation started (Gowdy & McDaniel 1995). Nonetheless, since the 1960s human perspective to the environment evolved significantly. From humans being initially seen as mainly reactive on the environment (environment represents a danger to humans), they became then proactive to it (humans represent a danger for the environment), and later tried to become interactive with it (no danger if both humans and environment are handled carefully) thus moving from adaptation to sustainability to resilience.

In the mid 1980s already, Vitousek et al. (1986) raised the flag that, at global levels, massive interventions into nature change environmental conditions for living beings: the human appropriation of the terrestrial products of photosynthesis summed up to nearly 40% and a wide array of natural nutrient and mineral cycles were significantly accelerated by human beings. Based on these kinds of observations, the late 1980s almost logically became a fruitful period for elaborating mitigation approaches for dealing with human impact on the environment.

In 1989, in their seminal article ‘strategies for manufacturing’[20] published in Scientific American, Frosch and Gallopoulos (1989) popularised the idea that ecological systems could be an analogue for industrial systems, suggesting that manufacturers who take in raw materials, generate products, and emit wastes could optimise their energy and materials consumption, minimise waste generation, and be more responsive to total environmental concerns by acting more like a living ecosystem. They proposed the concept of ‘industrial ecosystems’, systems that mimic the way nature flows work, analogous in its functioning to a community of biological organisms and their environment. Although they considered this analogy between the industrial and the biological ecosystems as not perfect, they claimed that much could be gained if the industrial system were to mimic the best features of the biological analogue. For instance, waste from one industrial process can serve as the raw materials for another, thereby reducing the impact of industry on the environment. Moreover, they suggested each process and network of processes of the industrial ecosystem should be viewed as a dependent and interrelated part of a larger whole. In other words, the traditional model for industrial activity in which individual manufacturing processes take in raw materials and generate products to be sold plus waste to be disposed of should be transformed into a more integrated model, that is, the so-called industrial ecosystem.

This suggests that manufacturing processes in an industrial ecosystem simply transform circulating stocks of materials from one shape to another; the circulating stock decreases when some material is unavoidably lost, and it increases to meet the needs of a growing population. Like their biological counterparts, individual manufacturing processes in an effective industrial ecosystem contribute to the optimal function of the entire system and cannot be considered in isolation. Consequently, where wastes are continuously reused such that there is no ‘waste’ then clearly waste reduction and eco-efficiency become irrelevant. More concretely, a process that produces relatively large quantities of waste that can be used in another process may be preferable to one that produces smaller amounts of waste for which there is no use. Industrial symbiosis is a typical context where such approach is meaningful[21].

As per Erkman analysis in his book dedicated to industrial ecology (IE) (Erkman 2004), there are many reasons for the strong interest that has been created by Frosch and Gallopoulos’s article: the prestige

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[19] Related research outputs:

- For a general introduction of the field of industrial ecology, see Annex A-§6.2 and §7 of Oïkosmos Report .
- For an overview of the operational aspects of industrial ecology, see Annex C2a-§7 in BELiSSIMA Phase A TN118.1.4.

[20] The original title proposed by the authors was “Manufacturing - the industrial ecosystem view”, but was not accepted!

[21] Cf §3.1.

of Scientific American, Frosch's reputation in governmental, engineering and business circles, the weight carried by the authors because of their affiliation with General Motors, and the general context, which had become favourable to environmental issues, with, among other features, discussions about the Brundtland Commission report on sustainable development. The article manifestly played a catalytic role in the diffusion of the concept IE, as if it had crystallised a latent intuition in many people, especially in circles associated with industrial production, who were increasingly seeking new strategies to adopt with regard to the environment. Although the ideas presented in the article were not, strictly speaking, original, the Scientific American article can be seen as the source of the current development of IE. In the following years, other authors such as Robert Ayres, Brad Allenby and Thomas Graedel began to write papers disseminating the idea in both academic and business circles.

Like any modern field of engineering offered within engineering curricula, IE strives to put a solid science-based foundation under itself (Ehrenfeld 2007). Biotechnology builds on biology; chemical engineering is grounded in chemistry and physics. The primary source for IE, as the name suggests, is scientific ecology, although it also draws on other sciences, including thermodynamics, physics, and chemistry.

As described by Erkman (2004), apart its rigorous conceptual framework from scientific ecology, IE is characterised by several other specificities: its main concern is biophysical substratum of human activities (material flows and stocks); it benefits from an operational strategy aiming for the implementation of sustainable development; it is leveraged by a collective and cooperative strategy at a systemic scale, with an integrated view of all the components of the industrial economy and their relations with the biosphere); and it considers technological dynamics as crucial (but not exclusive) for the transition to a viable industrial ecosystem.

After over three decades of consolidation of their discipline, industrial ecologists have developed since the late 1980s operation tools for a better understanding of material flows circulation and realistic construction of material balances at different scales within industrial ecosystems. In addition, their associated activities also encompassed preparation of life cycle analysis, optimisation of industrial processes, elaboration of models, as well as risk assessment for adequate decision-making in the prospects of sustainability and circular economy. At the core of their field of interest, industrial ecologists put some strong emphasis in deepening the concept of nature as a model for IE initiated by Frosch and Gallopoulos. This analogy between natural and industrial ecosystems is precisely the focus of the next section which reviews the waste analogy (§2.2.2.1), biological and industrial organisms (§2.2.2.2) and metabolisms (§2.2.2.3) and finally discusses considerations for energy and matter dissipation (§2.2.2.4).

2.2.2 The analogies between the natural and industrial ecosystems (RO1.1)

Since the 17th century, economic theory and biology (including its sister discipline ecology) can be said to have co-evolved, so dense are the mutual links in their theories (Bey 2007). According to Wells and Darby (2006), parallels between ecological systems and economic structures include the facts that: 1) both occur in and are an integral component of local and global communities; 2) multiple interactions take place between the constituent parts; 3) stability and disturbance can alter the course of events; 4) the dominance of one or more players will impact outcomes; 5) competition is a fundamental element; and 6) both are reliant on and have a major influence on resource flows and cycles. Historically, it should be mentioned that a major difference relies on the fact that most economic theories assume unlimited growth, regardless of limited resources, whereas ecology theory assume self-regulation of its ecosystems to the environment carrying capacity[22].

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[22] Cf §3.8 on evolution principles.

Vincent (2000) noted that often, when you tell someone that an idea comes from nature, you are halfway toward selling it. This is verified in a rising number of company strategies and a growing number of industrial decision-makers and policy-makers starting to feel as ecologists (Bey 2001) whereas in the past, much of industry's inertia towards ecological ideas and restructuring could be attributed to an unwillingness to communicate with scientific ecologists.

Traditionally, when industrial ecologists refer to nature as a model, nature is employed as a model explicitly or at least implicitly. The concept of IE is based on an analogy (not an exact correspondence) between 'natural ecosystems' and the man-made industrial system. This frequently proclaimed persuasive analogy is sometimes phrased in terms of a natural ecosystem metaphor. One of the big questions is how far these analogies and metaphors between systems can be taken, so that associated studies can implement ecological understanding adequately.

Isenmann (2003) discussed the IE perspective of nature as a model for understanding and optimising industrial processes. His conclusion was that such analogy was not completely neglected at the beginning of the 2000s, but still hidden and largely uncommunicated at a broad level, and in most cases relatively unquestioned and not made sufficiently clear. He argued that industrial ecologists use metaphors and analogies to gain fruitful insights (discovery) and to deliver new insights (application). Isenmann also explored the changing perspectives from an industrial ecosystem point of view, from using nature as a 'sack of resources' (perspective 1), to avoiding use of nature (perspective 2) towards learning from (perspective 3) and co-evolving with nature (perspective 4). By combining them, a significant change of how nature should be interpreted compared to other disciplines' views can be perceived, switching from mainly using nature as a mere store of material and energy towards learning from nature by selectively applying nature's smart solutions and services, through co-evolutionary strategies based on ecological principles.

According to Graedel and Allenby (1994), the insight that industrial systems should observe nature and learn from the structure and dynamics of natural ecosystems needs the application of systems science. Industry should reflect ecological and biological principles in the design and operation of its activities. Tibbs (1992) considers that this intention to 'learn from nature' by 'translating' or of 'copying' from natural systems into our economic system is what differentiates IE from classical engineering and economic approaches. Efficiency and productivity are to bring in dynamic balance with resiliency, ensuring continued natural capacity.

According to Levine (2003), industrial systems and ecological systems are far from unconnected and share analogous structures processes. Both are complex systems displaying many types of energy and material flow-regulating interactions, and undergoing continuous change.

For Erkman (2004), research on the nature, validity, relevance and limitations of the analogy between anthropised ecosystems (including industrial) and biological ecosystems has only recently begun, as previously corroborated by Graedel (1996) stating that cross-fertilisation of specialities or help to enlighten them remains to be seen.

Ehrenfeld (2003) considered that if metaphor provides an inspiration framework, only analogy provides a precise metric for measurement. Hess (2010) observed that some authors surprisingly appear to mix analogy and metaphor meaning, and gives an epistemological and a philosophical point of view for a deeper understanding of analogy, models and metaphors. In his opinion, IE community usually conceives that the industrial system should not be seen as separated from the biosphere, but rather as integrated into it. Consequently, a strong interdependence between man and nature considers that technology is at the service of this integration, and that by analogy, biological ecosystems serve as a model for the functioning of the industrial system. The means of this integration imply a closing of the technosphere on itself so as to preserve as much as possible the physical, biological and chemical cycles.

Initial attempts to view industrial activity with the images and tools of scientific ecology (or biological ecology) were somehow limited by its empirical speciality in which systems are complex, data sparse, and perspectives frequently confounded (Graedel, 1996). Nonetheless, parallels between biological and industrial ecology in several areas not only exist but seem natural rather than contrived. For example, organisms and ecosystems can be readily identified in both of them[23], and some organisms function as engineers in each system (Jones et al. 1994)[24], and this is the same for their respective products (Levine 2000).

There are several contributions of IE to engineering illustrating the beneficial employment of natural ecosystem metaphor and ecological (or biological) analogy. Gradual introduction of elements from natural ecosystems theory includes integration of the concept of 'food chains' (Frosch & Gallopoulos 1989) and 'circular systems'[25], arise with the popularisation of the terms 'industrial metabolism'[26] (Ayres 1994), as well as 'industrial symbiosis' (Graedel & B. R. Allenby 1994) (close industrial complexes in which the individual enterprises interchange their wastes and by-products with others)[27]. Together with diversity concepts, these classical analogies have become central pillar in IE literature, whereas ecological succession (B. R. Allenby & Cooper 1994) and energy dissipation (Kay 1991) have not received the same attention.

The list below gives an insight how references to nature as a model were done by the IE community chronologically from the late 1980s to the early 2000s, when these analogy-metaphor discussions as theoretical concepts of IE research were booming within the community. The list is adapted and largely extended after Isenmann (Isenmann 2003):

1. IE functions as an analogue of biological systems (Frosch & Gallopoulos 1989);
2. IE takes the pattern of the natural environment as a model (Tibbs 1992);
3. Learning from nature means to take private lessons in ecology (Simonis 1993);
4. Natural ecosystems as no-waste ecology (Richards et al. 1994);
5. The ideal anthropogenic use of (…) materials (…) would be one similar to the biological model (Graedel & B. R. Allenby 1994);
6. Nature is the measure of man; nature as the principal shaper of global human activity (Socolow 1994);
7. Nature is instructive to explore in some detail what an industrial ecosystem could involve (Andrews et al. 1994);
8. A mature natural ecological community operates as waste minimising system (Ayres 1994)
9. Sustainable economic structure will resemble a mature biological community (B. R. Allenby & Cooper 1994);
10. Nature understood as master of recycling (Graedel & B. R. Allenby 1994);
11. Industrial ecosystems designed from 'scratch' to imitate nature (Ayres & Simonis 1994);
12. The industrial system can be seen as a certain kind of ecosystem (Erkman 1997);
13. Scientific ecology insights must be important to the evolution of industry and society and be of benefit to both environment and economy (Erkman 1997);
14. IE implies that models of non-human biological systems (...) are instructive for industrial systems (Wernick & Ausubel 1997);
15. In the long run, cultural evolution, and economic development, cannot progress without considering fundamental laws and principles of nature (Ring 1997);
16. Orienting economic activities towards ecological principles of system organisation (Ring 1997);

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[23] Cf §2.2.2.2.
[24] Cf §3.6.
[25] Cf §3.4.
[26] Cf §2.2.2.3.
[27] Cf Annex A-§6.3 and Annex C2.1-§7.2.

17. IE asks whether Nature can teach industry ways (…) in minimising waste and in maximising the economical use of waste (Ausubel 1998);
18. The concept of IE (…) [is] based here on the biological analogy (B. Allenby 1998);
19. Nature as cyclical economy without waste (Manahan 1999);
20. It is characteristic for IE to look to the natural world for models of (...) efficient use of resources (Cleveland 1999);
21. Natural ecosystems (…) offer the only (…) example (…) of long-lived, robust, resilient living systems (Ehrenfeld 2000);
22. IE (…) looks to the natural world for models of highly efficient use of resources, energy and byproducts (Journal of Industrial Ecology 2000);
23. Famously, industrial ecologists look to biological ecosystems as analogies or metaphors in the study of production and consumption (Côté 2000);
24. As a consequence, it may be that valuable knowledge can be deduced from studying the patterns they follow and that this knowledge should be integrated in our management policies by ‘implementing nature’s lesson’ (Hall 2000);
25. IE means to understand nature as a teacher and ‘learning from nature’ (Norwegian University of Science and Technology IE Programme, 2001);
26. Just as in the food chain processes of natural ecosystems, we must create networks of resource and waste use in industrial ecosystems (Erkman 2001);
27. Natural systems cycle resources extensively (Lifset 2002);
28. The industrial metabolism concept can be applied so that it resembles most closely that of a sustainable biological organism, with low material input, throughput and output (Durney 2002);
29. Nature as a bio-cybernetic life support system (Isenmann 2003);
30. IE dream that, as in natural systems, waste equals food and that linking one company’s ‘throw-aways’ to another’s need will provide better environmental and business outcomes (Cohen-Rosenthal 2004);
31. IE is a strategy to promote the reduction of the environmental impact of industry by learning from an analogy with natural systems (Deutz & Gibbs 2004).

2.2.2.1 *Waste analogy*

Several of the above perspectives claim about the minimisation or the absence of waste in (mature) natural ecosystem (above-listed quotes 4, 8 and 17) or state that waste should equal food (quote 30), while this is not always necessarily the case. Many well-meaning environmentalists seem to imagine that the biosphere is a perfect recycler and suggests that the industrial world should imitate nature in this regard, so to achieve ‘zero emissions’ in the industrial landscape by recycling all wastes.

In an essay on theoretical and practical limits to a circular economy, Bey (2007) considers natural ecosystems as circular systems is idealised and includes some critical simplifications: *‘in natural systems, there are indeed linear material flows, some of great importance, leading to sediments that have accumulated for eons and still continue to do so. Sediments of animal shells, the formerly vegetal matter of mezozoic plants that today is the supplier of fossil fuels, methane emissions of ruminants (a greenhouse gas much more potent than CO_2), and most importantly oxygen that accumulated in the atmosphere as a waste product of early photosynthesis in the paleozoic era. This oxygen, one of the most potent cell toxins, required the development of organisms at a higher state of evolution.’*

This point of view is confirmed by Margulis (1999), who *‘suspect that bacteria first removed the hydrogen they needed for their bodies directly from air. Later they took up the hydrogen sulphide belched up from volcanoes. Eventually, blue-green bacteria wrenched hydrogen atoms from water. Oxygen was expelled as a metabolic waste product. This waste, at first disastrous, eventually powered life's continued growth. New wastes test life's tolerance and stimulate life's creativity. The oxygen we need to breathe began as* *a toxin; it still is. The oxygen release from millions of cyanobacteria resulted in a holocaust far more profound than any human activity. Pollution is natural. The cyanobacteria's waste became our fresh air. We human obtain the hydrogen we require by eating plants or other animals. We cannot do without. Often newly evolved beings grow and expand rapidly by exploiting the energy food supplies, or waste of others.'*

So while most biomass is recycled fairly quickly, nature is sometimes highly wasteful, as exemplified by the fact that several economically important industrial resources are accumulations of unrecycled biological wastes left over from the distant past. According to Ayres (2004), pollution is natural. 'Waste not' is an exhortation, not a description. Nonetheless, the existence of considerable amounts of coal and oil, resulting from dead organic matter that was deposited in prehistoric times in oxygen-poor environments, such as bogs or sea bottoms, not supporting adequate numbers of decomposers, indicates that even in ecosystems, recycling and reuse is never 100% efficient, according to the 2nd law of thermodynamics. Ayres (2004) cites numerous other examples: *'Iron ore is a leftover from the oxidation of the ferrous iron formerly dissolved in the oceans; chalk, limestone and marble are leftover from the shells of tiny marine organisms. Phosphate rock may be a residue from millions of generations of shark's teeth. Water, CO_2, and oxygen are recycled via an external reservoir (the ocean and/or the atmosphere). Nitrogen, phosphorus and potassium are partially recycled by decay organisms and bacteria through dead biomass and another nonliving reservoir (humus and topsoil). Other elements such as sulfur, calcium, chlorine and trace metals are not efficiently recycled at all, except via slow geological processes. The idea of "zero emissions" is based on the (false) idea that every biological waste is "food" for some other organism (by extension it is the food of the industrial system !). This is true, essentially, only for carbon-based organic materials and, especially, the well-known carbon–oxygen cycle. Just as some biowastes are not recycled, many industrial wastes cannot be economically recycled.'*

Even low survival among eggs and young among most offspring can be seen as wasteful. In such cases, waste is the basis of life. Similarly, the reproduction of the oak tree is hugely wasteful, with millions of acorns for only a few plants. However, this waste forms the basis for a great many life forms that depend upon acorn production. An extreme example is yeast, which is sometimes killed by its own waste products (Wells & Darby 2006).

The above-mentioned facts contradict the vision of industrial ecologist like Korhonen (2004), claiming that *'[i]n nature, harmful flows do not concentrate (with the exception of some toxins) in a way that is the case when industrial wastes are released to nature as a result of societal or industrial activity or processing.'*

The next two analogies explored hereafter applies to biological and industrial organisms (§2.2.2.2), as well as to biological and industrial metabolisms (§2.2.2.3).

2.2.2.2 Biological and industrial 'organisms'

Graedel (1996) examined the structural framework of biological ecology (BE) and the tools used for its study. He demonstrated that many aspects of biological organisms and ecosystems (food webs, engineering activities, community development) do have parallels in both 'industrial organisms' and ecosystems. Graedel stated further that some of the tools of BE appear to be applicable to IE, and vice versa. He discussed how to explore the biological analogy in increased depth, with the idea that it holds more value than just the cyclisation of resources.

He defined elementary units of study in BE as the biological organism (BO), an entity internally organised to maintain vital activities and capable of independent activity. A BO can take actions on its own behalf, utilises energy and material resources, releases waste heat (excess energy) and materials residues into the surroundings (feces, urine, exhaled breath, etc.). A BO is capable of reproduction (but number of offspring varies enormously between specis), it responds to external stimuli (to such factors as temperature, humidity, resource availability, potential reproductive partners, …) and it has a variable, but finite, lifetime. All multicellular organisms originate as one cell and move through stages of growth.

Graedel characterised industrial organisms (IO) such as a factory (incl. its equipment and workers) from the perspective of the biological organism. Like BO, IO convert incoming energy and materials streams to useful products. IO release waste heat and materials residues (solid and liquid waste, gaseous emissions). If IO are capable of reproduction: an IO is not designed and constructed for the purpose of re-creating itself, but to create a nonorganismic product (such as a pencil). New IO are created by contractors whose job is to produce any of a variety of factories to desired specifications rather than to create replications of existing factories. If reproduction is the generation of essentially exact copies of existing organisms, then IO do not meet the definition. If substantial modification (mutations) is allowed for, we can recognise that copies or similar organisms are indeed generated. However, IO reproduction is not a function of each individual organism itself, but of specialised external actors.

Whereas BO and species react to natural stimuli such as lack of food, the presence of a predator, the secretion of a hormone, or to weather conditions, storm, fires and diseases, human actors and IO respond to external stimuli/factors (resource availability, tastes, preferences, potential customers, prices…). Eventually, IO do not need to keep specialised and can change from one product or business to another. By contrast, most highly specialised BO cannot change their behaviour except over a long (evolutionary) time period (Ayres & Simonis 1994). Does an IO move through stages of growth? Though few factories are unchanged during their lifetimes, they do not follow the orderly or predictable progression of life stages of the BO. IO has a finite lifetime. One of the key signatures of both BO and IO, is that it is involved in resource utilisation after, as well as during, its manufacture. Finally, in natural ecosystems, BO are expert at working within or responding to their environmental conditions. In contrast, IO strive to define the environment for themselves.

2.2.2.3 Biological and industrial metabolisms

All living organisms have a metabolism: in order to grow, survive and reproduce, they consume (and then reject) resources in the form of matter and energy. Naturally, the human species is no exception to this rule. The word metabolism, as used in its original biological context, connotes the internal processes of a living organism. The organism ingests energy-rich, low-entropy materials (‘food’) to provide for its own maintenance and functions, as well as a surplus to permit growth and/or reproduction. The process also necessarily involves the excretion or exhalation of waste outputs, consisting of degraded, high-entropy materials.

Cellular metabolism is the set of chemical reactions that occur in living organisms in order to maintain life[28]. These processes allow organisms to grow and reproduce, maintain their structures, and respond to their environments. Metabolism is usually divided into two categories. Catabolism breaks down organic matter, for example to harvest energy in cellular respiration. Anabolism, on the other hand, uses energy to construct components of cells such as proteins and nucleic acids[29].

The chemical reactions of metabolism are organized into metabolic pathways, in which one chemical is transformed into another by a sequence of enzymes (see Figure 5). Enzymes are crucial to metabolism because they allow organisms to drive desirable but kinetically unfavourable reactions by coupling them to favourable ones, and because they act as catalysts to allow these reactions to proceed quickly and

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[28] As defined by Tocris Bioscience on https://www.tocris.com/cell-biology/cell-metabolism as of 22.03.2020.

[29] As described on Wikia.org: https://psychology.wikia.org/wiki/Metabolism as of 22.03.2020.

efficiently. Enzymes also allow the regulation of metabolic pathways in response to changes in the cell's environment or signals from other cells. In ecology, metabolism could be seen as material and energy flows in food webs.

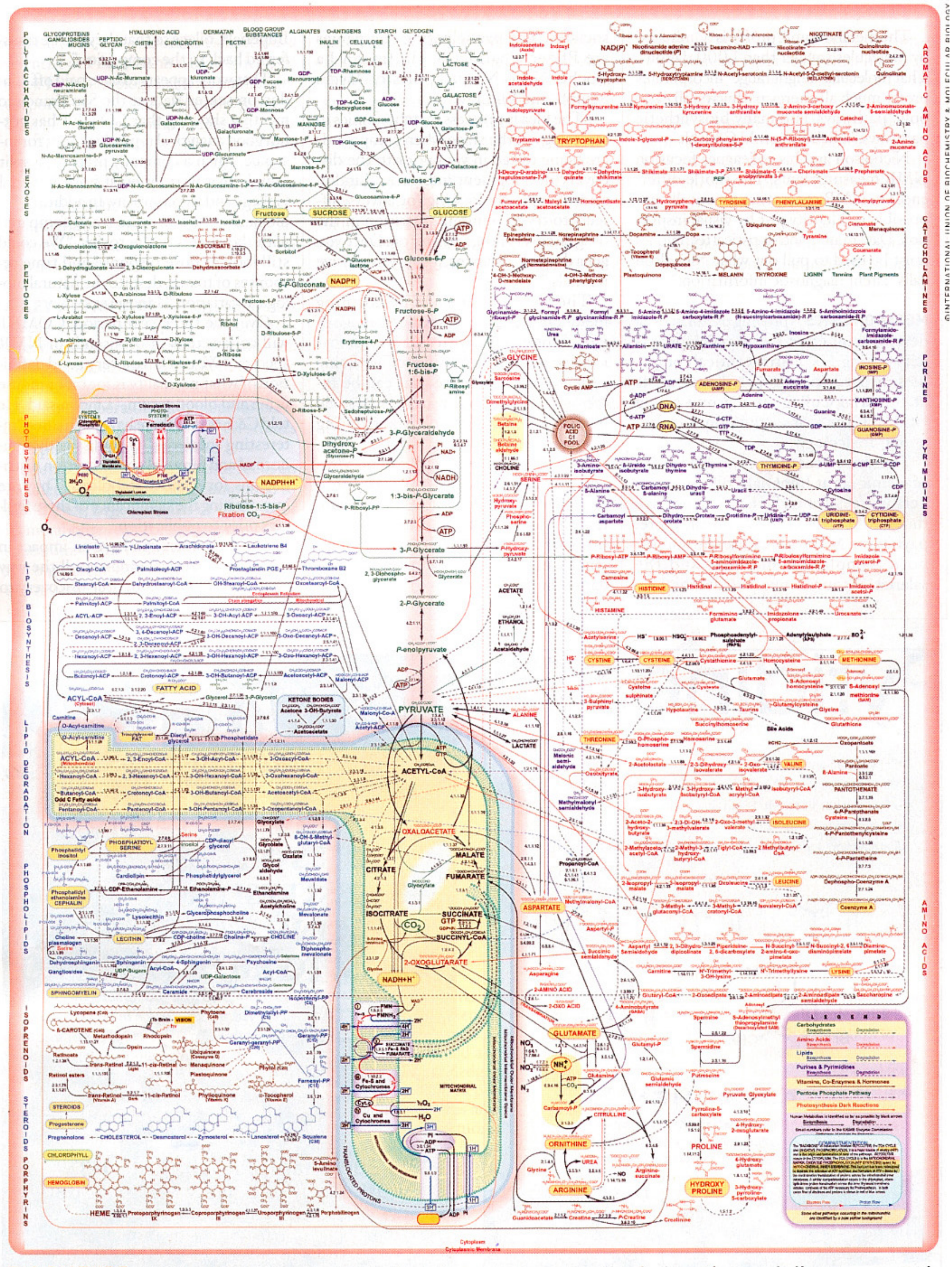

Figure 5: Overview of cellular metabolic pathways.
Cellular metabolic pathways are extremely numerous and intermingled, and provide to biological organisms their versatility and adaptation capacity to change along their evolution. These pathways are very conserved in evolution between species from simple prokaryotic to complex multicellular eucaryotic ones. They are at the base Source: International Union of Biochemistry and Molecular Biology.

From the perspective of IE, if we want to make appropriate changes to the functioning of the current economic system, it is important to understand its metabolism. Both biological and industrial systems are characterised by recognisably similar 'metabolic' functions such as: 1) ingestion, digestion, excretion, reproduction and growth, corresponding to the intake of raw materials; 2) primary processing and separation of valuable fractions from wastes; 3) waste disposal; 4) mass production of an artefact from blueprints; 5) growth obviously applies to organisms or populations as well as firms and economies. These metabolic correspondences have prompted a number of explorations on the industrial side, especially focused on mass and energy (exergy) flows in the economy (Ayres 2004).

Erkman (2004) defined 'industrial metabolism' as the whole of materials (the physical vehicle of interactions) and energy flows going through the industrial system. It is studied through an essentially analytical and descriptive approach (basically an application of material mass balance principle), aimed at understanding the circulation of the materials and energy flows (and stocks) linked to human activity, from their initial extraction to their inevitable reintegration, sooner or later, into the overall biogeochemical cycles. As the expression 'industrial metabolism' is often misunderstood, the wording 'metabolism of economic activities' or 'physical/material accounting' or 'material flow analysis' tends to be used more frequently. In view of the industrial metabolism, the main danger in a long-term perspective is the disturbance of major cycles of the biosphere, and the depletion of natural resources or the inconvenience of pollution. The concept of industrial metabolism is applicable to kinds of self-organising entity such as a manufacturing enterprise or firm. As described above, a firm can be seen as the economic analogue of a living organism. Some of the differences previously discussed[30] include especially the fact that BO reproduce themselves; firms produce products or services, not other firms (except by accident). In additions firms can change from one product or business to another.

For industrial metabolism case studies at national, regional and local levels in industrial countries, consult the work of Ayres and Simonis (1994), for others at the level of developing countries see the work of Erkman and Ramaswamy (2003). For application of industrial metabolism to the sector of biorefinery, see Octave and Thomas (2009).

2.2.2.4 Considerations about energy and matter dissipation

In addition to the features discussed earlier[31], there is a compelling analogy between biological organisms and industrial activities - indeed, the whole economic system - not only because both are materials-processing systems driven by a flow of free energy (Georgescu-Roegen 1971), but because both are examples of self-organising dissipative systems in a stable state, far from thermodynamic equilibrium (Ayres 1988).

A better understanding of resource flows in IE terms needs discussion of the energetic nature of waste exchanges in industrial ecosystems (Bey 2007). For these flows to be truly circular, the wastes and by-products cycled would have to be reused at an energetic level equivalent to the one they came out of. If this is not the case, any exchanges would only be a linear depletion of free energy, albeit with a higher efficiency, as the free energy content of resources diminishes every time they are utilised ('entropy increases'). Such a pseudo-circle as envisaged in many projects in IE should properly be called a 'cascade' where material flows reach a final state of waste (that is, without any use) that will be deposited. A circular system deserving this name would be one that closes entropy cycles (O'Rourke et al. 1996) and replenishes the free energy content of wastes to such an extent that they again become

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[30] Cf §2.2.2.2.

[31] Ibid.

valuable resources and can be utilised in the original production process or in one at an equivalent free Gibbs energy level. This is the reason why O'Rourke et al. criticise IE's misplaced and simplistic focus on matter, where, they hold, it is the *free energy content of matter* that is of primary importance for the evaluation of material flows in industrial ecosystems in order to avoid a rundown of non-renewable resources.

A number of bioeconomists such as Nicholas Georgescu-Roegen (1971), Robert Ayres (1988) and Matthias Ruth (Ruth 1996), as well as industrial ecologist Suren Erkman (1997; 2004) stressed the point that the majority of the global economic system's components behave in a dissipative manner. It is therefore not the exchange of goods and services against payment that should be regarded as the true characteristic of economic relationships on a global level, but the dissipation of energy, largely from non-renewable sources, and matter.

Many industrial wastes can be recycled, albeit not perfectly, and sometimes only by the application of significant amounts of energy from somewhere outside the system. In this respect, several authors have discussed the thermodynamic limits of chemical transformation which either render complete recycling of all industrial products impossible, or would necessitate at least an enormous amount of energy that must not come from non-renewable sources or whose production must not create material waste (Ayres 1998; Bianciardi et al. 1996).

Nature recycles carbon and oxygen, by means of the carbon cycle, which is driven by photosynthesis, i.e. by solar energy and by the respiratory chain. However, there is no analogy to the carbon cycle in the industrial world. In fact, there is no analogue of photosynthesis in the industrial world that is widely spread. For Ayres (2004), this essential difference alone could invalidate the analogy between ecology and economics. One can counter-argue that since the early 2000s the topic of large-scale valorisation of CO_2 as a resource has been increasingly studied (Erkman 2003). The associated technologies related to the use of this atmospheric global carbon wealth are numerous, and go to the extent of mimicking photosystems artificially through nanobiotechnologies techniques. Meylan et al. (2015) gave an overview of the field of CO_2 utilisation in the perspective of IE. They analysed capture at large sources, direct air capture and a bioenergy with carbon capture, as well as utilisation through processes such as solar fuel synthesis, mineralisation, polymer synthesis and biological utilisation. Oïkosmos Report describes the strategies for CO_2 valorisation that could be relevant in the context of ACE and CH[32].

2.2.2.5 Final considerations

Chapter 2 examined the conceptual background of this research. Initially, it described key elements from IE, starting with a brief historical perspective of the ecology and ecosystem concepts (§2.1), followed by a focus on the 'ecology' of IE (§2.2). The latter section first illustrated the early years of the young research field of IE (§2.2.1). Later, it discussed the analogy between the natural and industrial ecosystems (§2.2.2, RO1.1), notably by reviewing the waste analogy, biological and industrial organisms, biological and industrial metabolisms and considerations for energy and matter dissipation.

Putting this analogy under further perspective, one can consider that still for some researchers, IE has proven to be more adept at closing materials cycles than promoting a fundamental paradigm shift in industry-ecology relations (Bey 2001). As noted by Erkman (2004), IE is (very) young, and its research agenda for engineering sciences and natural sciences, is just beginning to be developed. As a priority, it will be up to ecological scientists and epistemologists to explore in depth the relevance and limitations of the analogy between the industrial and biological (eco)systems.

Nielsen (2007) compared natural systems and industrial-societal systems using ten target areas

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[32] Cf Annex A-§7.4.4.

(complexity, evolution, compartmentalisation, flows and processes, feedbacks and controls, cycling, network properties, organisation and hierarchy, diversity and open systems and dissipation) to increase knowledge, strengthen the foundations and better implement IE. He saw an evolution of a man-made industrial system that imitates the functional ecosystems principles as an ingenious strategy to follow. Nielsen considered that such eco-mimetic development should lead to more sustainability for our modern society thanks to its panel of practical approaches and tools such as industrial symbiosis and metabolism to cite just a few.

As highlighted in the previous sections, IE concept represents very challenging initiatives and expresses considerable ambitions. Particularly, the considerable knowledge developed by scientific ecology on the functioning and regulation of ecosystems has many elements that could be relevant in guiding the industrial system towards a sustainable path to long-term, consistent with the functioning of the biosphere. In return, the study of the industrial system as a special case of ecosystem could contribute to the enrichment of scientific ecology itself (Erkman 2004). Nonetheless in 2021, even though most industrial ecologists are aware of and are practising some points in ecosystem theory, far from all principles, have been exploited.

Some of the characteristics of ecosystems that makes it difficult to fully apply ecological theory into the construction of IE theory and practice (Jørgensen 2002) are as follows: 1) there are a great number of organisms and species and they are all different; 2) the high number of species gives an extremely high number of possible connections and different relations; 3) the amount of feedback and regulations is extremely high and makes it possible for the living organisms and populations to survive and reproduce in spite of changes in external conditions; 4) the feedbacks are constantly changing; 5) ecosystems show a high degree of heterogeneity in space and in time; 5) ecosystems and their biological components, the species, evolve steadily and in a long-term perspective towards higher complexity.

In addition, the following observations should be made:

- To date, even after years of development and implementation of sustainability and circular economy concepts[33], only few biologists are represented among the traditional IE community members. Education of engineers, economists, managers and natural scientists remains crucial, in order to deal with a serious cultural problem: due to their respective curricula, on the one hand, ecologists (not only political ecologists, but scientific ecologists as well) usually do not know much about the industrial system, and on the other hand, engineers and people from industry in general, have reversely a very naive view of nature and are – still – sometimes very defiant against ecologists and ignorant about scientific ecology. Allenby and Cooper were two of the first to claim that increased communication between ecologists and industrial ecologists than what has occurred to date was required (B. R. Allenby & Cooper 1994);
- Over 98% of the papers published in international journals fully dedicated such as Journal of Industrial Ecology[34] or Progress in Industrial Ecology[35], or encompassing the field of IE, like for instance Ecological Economics[36] and Journal of Cleaner Production[37] focus mainly on methodologies and tools of industrial symbiosis, material flow analysis (MFA) and life cycle analysis (LCA) when treating about IE. In other words, less than two percents of all the papers were not derived from or reasonably related to other analogy aspects related to systemics,

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[33] Cf §14.

[34] Journal of Industrial Ecology website: https://onlinelibrary.wiley.com/journal/15309290. Retrieved on 01.05.2021.

[35] Progress in Industrial Ecology journal website: https://www.inderscience.com/info/inissues.php?jcode=pie. Retrieved on 01.05.2021.

[36] Ecological Economics journal website: https://www.journals.elsevier.com/ecological-economics. Retrieved on 01.05.2021.

[37] Journal of Cleaner Production website: https://www.journals.elsevier.com/journal-of-cleaner-production. Retrieved on 01.05.2021.

evolution, dissipation or compartmentalisation (see next sections). This means that much, if not virtually all, of research on and applications of IE focus on metabolism (for understanding material flows or for environmental impact assessment, often comparing alternatives) and structural relationships and systems (symbiosis) (Ehrenfeld 2007);

- In principle, IE has a multidisciplinary and integrative nature, it sits not beside existing reductionist disciplines, but somewhat above them, as a metadiscipline and complementary discipline (B. Allenby 1999). Nonetheless, among the publications that analyse the ecological analogy for industrial systems, the great majority, if not all, focus on exploring ecosystem and ecological systems only on a medium to large scale, ignoring what could be learned, from smaller scale of biological systems, from (molecular) cell biology or physiology up to miniaturised ecosystems[38]. Environmental sciences and engineering encompass a number of other disciplines such as chemistry, physics and mathematics, but surely at their core are all the biological sciences, from conservation biology and ecology to molecular and cellular biology. In order to further develop the IE concept, looking at IE through a broader biological or scientific ecology lens could lead to a better understanding of the analogy between developing and mature ecosystems and widen the scope of ecology to systems biology.

Several analytic approaches and tools of scientific ecology, especially in the context of ACE, may well be useful in advancing the much younger IE (food web analysis and metabolism are examples, see §2.2.2.3). Conversely, IE has tools of its own, despite its youth, and some of them may play useful roles in natural ecosystems (see notably Annex A-§7.2.3 and §7.2.5 on MFA and LCA). Seen from the perspective of a biologist, what other parallels can be drawn between the principles of ecosystem functioning as well as of the principles of IE? One of the main objectives of this work is precisely to explore deeper what key concepts from scientific ecology fields - and life sciences in general - can (or cannot!) be further consolidated or newly transferred, and ultimately implemented to the whole of the industrial system.

The study on circular systems such as artificial closed ecosystems (ACE)[39] and closed habitat (CH)[40] in the perspective of both scientific and industrial ecology is therefore at the heart of this PhD thesis. Especially as the reception of ACE theory in the direction of IE has been rather preliminary so far. Also, the research on space advanced life support systems (space ALSS) appears to be one of the most promising ones, as an extreme example of industrial ecosystem.

The combination of the research outputs of this work is an attempt to clarify the potential, relevance and interest of ACE and CH, and fill some potential research gaps thanks to a systematic review of scientific and industrial ecology approaches.

As a first step in this direction, the next chapter precisely proposes and analyses key concepts for ACE analysis in the perspective of IE.

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[38] See notably Annex A-§8 for numerous examples of such research themes.

[39] Cf §3.1.

[40] Cf §13.

3 Key concepts for ACE analysis in the perspective of IE (RO1.2)

Chapter 3 proposes key concepts for ACE analysis in the perspective of IE (RO1.2). It first positions ACE in the context of scientific and industrial ecology (§3.1). Next, it provides essential principles of systems to better apprehend ACE (§3.2) by introducing the notions of system feedback and control. Later, sections §3.3 to §3.9 explore key concepts for ACE analysis in the perspective of IE and investigate their relevance for consolidating the conceptual foundations of IE (RO1.2). The examined concepts encompass ‘interactions’ on artificially predefined symbioses in circular systems, ‘cycling’, ‘biodiversity’, ‘compartmentalisation’, ‘reproduction’ and ‘evolution’.

3.1 ACE in the context of scientific and industrial ecology[41]

Artificial Closed Ecosystem (ACE) can be considered as a simplified and miniaturised ecosystem operating in closed-loop. It uses biological organisms (bacteria, algae, plants, etc.) to regenerate air, water and food with the objective of complete self-sufficiency. Humans are part of the ACE discussed in this work. Thus, ACE must provide extensive features that are essential and vital for their survival. Microorganisms cultures are typically employed to recycle water from wastes; higher plants are an essential source of fresh food through cultivation and harvesting, water is also partly recycled through plant evapotranspiration, and oxygen is produced by higher plants or microalgae photosynthesis. More specifically, the system ensures 1) the supply of water (drinking water and personal hygiene); oxygen and food (essentially vegetal biomass) for the crew, and 2) the recycling, the regeneration and/or the valorisation of organic wastes (faeces, non-edible parts of plants), air (exhaled CO_2) and wastewater (including urine). ACE recycling processes take place in a highly controlled environment, with immediate time horizon, and focus in particular on carbon, hydrogen, oxygen, nitrogen, sulfur, and phosphorus contents, that usually represent over 95% of the matter being recycled. Nevertheless, taking into account the crucial role of numerous trace elements, their study is also necessary. In ACE, the water system is a major constraint in terms of mass. Indeed, water can account for over three fourths of the total mass of consumables, or even more if washing and cleaning water is included (Grigoriev et al. 2010).

De Groot et al. (2002) mapped ecosystem functions into four primary categories, which can be applied to ACE: regulation (ACE health maintenance function such as gas, nutrient and climate regulation, water supply and waste treatment, pollination), habitat (refuge and reproduction habitat to ACE species), production (biomass and metabolites production, providing goods for human and other ACE organisms consumption such as food, raw material, as well as genetic, medicinal or ornemental resources) and information functions (providing opportunities for spiritual enrichment, recreation and aesthetic experience).

In a nutshell, ACE do not encapsulate pure nature but a selection of engineered pieces of ecosystemic elements. The succession of ACE compartments (e.g. bioreactors, plant growth chambers) aims at harnessing the capacities of selected microbial and plant strains and communities, in order to achieve a total and uninterrupted conversion of human wastes into breathable atmosphere, potable water and edible biomass.

ACEs, despite their lower biodiversity compared to natural ecosystems, are able to operate at a spatial scale of intermediate – or meso – complexity (Erkman & Chèvre 2006). The prefix *'meso'* implies that ACEs are of an 'intermediate' size[42], somewhere between:

✧ the lower hierarchical spatial scale, which corresponds to the study of *microcosms*. This is the scale at which most laboratory work relating to molecular and cellular biology takes place. The volumes involved in molecular hybridization experiments (DNA chips), for example, are on the order of a few microlitres. Bacterial cultures grow in nutrient solutions that range from several millilitres to a few litres. Culture chambers often have a small surface area (< 1 m^2 to several m^2), and soil samples frequently consist of several cubic decimetres.

- Advantages of this scale include: low operating costs; simplified conditions; good control over test conditions; good replicability of experiments; experiments generally take place over short periods of time; and evaluating microorganisms and plants is easier.

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[41] Related research outputs:

Artificial Closed Ecosystem (ACE) are described in the following research outputs of this study:

- Annex A-§4.1 of Oïkosmos Report on biological or bioregenerative life support systems (BLSS);
- Annex C2a-§8.2 of BELiSSIMA Phase A TN118.1.4.

[42] Cf Annex A-§7.3.1.2.

- Disadvantages include: tests are sometimes run on only one species; low level of interspecies interaction; limited scope for an (eco)systemic approach, since the reductionist approach is generally preferred; artificial conditions; little resilience in the event of a disruption (limited buffers); and high volume/flow ratio.

✧ the upper hierarchical spatial scale, which involves *macrocosms*. Here, researchers study ecosystems or organism populations growing in a test environment that is similar to their natural environment.

- Advantages of this scale include: nearly real-life conditions (more realistic); less clearly defined limits; relationships among a number of interspecies interactions can be studied, although this is more limited when it comes to relationships between microorganisms and plant species; and a robust testing environment.
- Disadvantages of this scale include: higher testing costs; more time required for experiments; high level of complexity (number of species, larger size and volume, etc.); limited ability to change test parameters and regulate environmental conditions; little control over system inflows and outflows; difficult to trace various elements (the metabolism of material flows); and less accurate modelling.

In view of the above considerations, ACEs can be considered as *mesocosms* with the following features[43]:

- highly confined;
- size average: larger than a test tube but smaller than the earth and most natural ecosystems;
- can be used to run short-, medium- and long-term experiments;
- better defined spatial limits;
- high level of control over inflows and outflows;
- a high level of control in general, giving researchers a free hand in setting some or all of the testing environment parameters (relative humidity, temperature, pressure, CO_2 concentration, level of pollutants, etc.);
- intermediate biodiversity with many different types of organisms (humans and superior microorganisms and plants) on more than one trophic level;
- the ability to induce organisms to interact thanks to highly controlled connections of flows between compartments; and
- a large number of sensors and other equipment to monitor and regulate key parameters.

The advantage of modelling and pilot-testing with a meso-level ecosystem (Figure 10) is that it makes it easier to monitor compounds (including inorganic compounds like phosphorus and water contaminants) throughout their respective cycles. They can be traced within the various compartments, pipes, installations, and processing and production equipment over long periods of time and over a large number of cycles. The limited space for buffer zones means that care must be taken when sizing them, in order to ensure long-term reliability.

Overall, ACE simulators[44] provide test conditions that are relatively close to those of actual natural ecosystems (macrocosms) but at a potentially lower cost (apart from the cost of developing and building the simulator itself) and with the short testing times typical of microcosms. ACEs reduce inherent complexity because they are encapsulated. And even though ACEs are still highly complex, owing in part to the vast numbers of experimental data they generate, it is easier for researchers to handle this complexity. Studying this type of closed ecosystem provides a unique opportunity to close the gap between prediction and observation within a ‘re-created’ ecosystem. This meso complexity level is precisely one of the major features that make the uniqueness (or unique selling proposition, USP) of the

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[43] Cf Annex A-§7.3.1.2.

[44] Cf §6.

ACE-based projects such as MELiSSA[45], BELiSSIMA[46] or Scorpius Prototype 1[47].

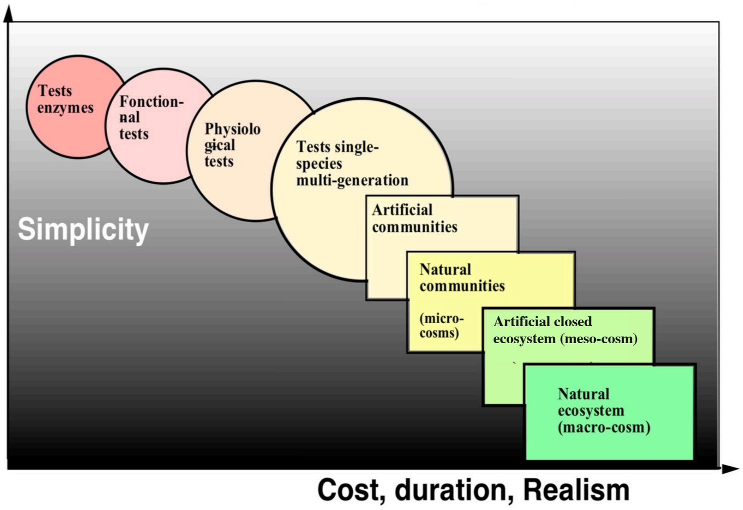

Figure 10: ACEs as mesocosms, system that operate at a meso spatial scale or meso level of complexity. Adapted from Erkman and Chèvre (2006)

ACE runs like a helpful red thread through both scientific ecology and industrial ecology with aim to further bridge the gap between their typical respective and reciprocal topics. Table 1 exposes the different environmental concerns from the point of view of an ecologist, an industrial ecologist and put them in perspective with the one of a life-support system researcher. Even if there is no strict relationship between the three views, it shows avenues that could be worth exploring as analogies between their respective fields and environments, the latter being the biosphere, the techno/econosphere and the artificial closed ecosystems.

Taken together, the large number of ACE-related topics makes that such circular systems demonstration clearly offers a remarkable platform for the conceptualisation and implementation of interdisciplinarity[48]. This involves the creation of new knowledge fields integrating the various disciplines, thus strengthening the IE theory, and consequently the field of ACE.

According to Hess (2010), the ambiguous frontier is thin to be able to say whether technological use within IE should be envisaged as a naturalisation of technologies or is it an artificialisation of nature. The selection or reprogramming of certain bacteria for particular tasks in an artificial system should be considered as a process of naturalisation of the technique. At the same time, the use a natural ecosystem function (e.g. nitrification) with the attribution by man of a specific function responding to a human need to treat yellow water shall be rather seen as an artificialisation of nature. In the latter case, the function could still be implemented in an ACE through a naturalised technology that would substitute itself to the natural ecosystem.

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[45] Cf §4.2.

[46] Cf §8.

[47] Cf §13.

[48] Cf Annex A-§16.

(a) The main concern of the ecologist (biosphere)	**(b) The main concern of the industrial ecologist (techno/econosphere)**	**(c) The main concern of the life support system researcher (ACE)**
System theory		Discussed in §3.2
Systemic principles, complexity; positive and negative feedbacks.	Pollution prevention, cleaner production, market offer and demand, rebound effect.	Systemic sustainability; self-sufficiency; system fine-tuning, system behaviour prediction; bioinspiration.
Matter and energy flows and processes		Discussed in §2.2.2.3
Metabolism / metabolic pathways; physical conditions; resources; biomass; nutrient exchange rate; open systems and dissipation and entropy.	Industrial metabolism and life cycle analysis; sustainable production and consumption patterns; energy efficiency.	Metabolism / metabolic pathways; environmental conditions; resources; biomass valorisation; nutrient recovery.
Anabolism / catabolism.	Manufacturing / waste management.	Food production / waste valorisation.
Natural product.	Industrial product.	High added value biomass (edible and inedible).
Interaction and networks		Discussed in §3.3, §3.7 and §13
Abiotic/biotic interactions; interspecific/intraspecific interactions; network properties.	Industrial symbiosis, presence of by-product exchanges, utility- or service-sharing agreements, competition within and across industrial sectors.	Symbioses between the ACE organisms, user-building symbiosis
Species life cycles and reproductive strategies.	Supply chain.	Human-induced life span of organisms and human-influenced reproduction and production levels' strategies
Trophic levels; food chain and food web.	Product life cycle.	Oscillation and divergence effect, back-up loops
Behaviours.	Business strategy, consumer behaviour, sustainable consumption.	Real-time monitoring of behaviours, user experience
Role of external inputs (nutrients, minerals, organisms) from outside its boundaries.	Role of imported materials, knowledge and capital.	Closedness limits these to information flows. In-situ resource utilisation in case of semi closure.
Ecosystem and cycles		Discussed in §3.4
Multispecies interactive cooperation for recycling; biogeochemical cycles.	Cycling of matter; reduction of waste disposal.	Integral recycling, circularity, closed-loop design.
Ecosystem structure		Discussed in §3.6 and §2.2.2.2
Compartmentalisation, organisation, hierarchy and spatiotemporal scale.	Sustainable growth and economic development.	Compartmentalisation, organisation, meso spatiotemporal scale.
Specie diversity and dominance.	Industry diversity and dominance.	Human-driven dominance of species depending on their role in the ACE.
Ecological niche and specialisation.	Business scope and activity sector	ACE functions and features.
Biological organisms.	Industrial organisms such as company or factory	Biological and industrial organisms.
Individuals.	Eco-industrial park.	CH (§13).
Environment.	Market, legal, economic and social issues; groups of processes	Exposome (Annex A-§7.3).
Ecosystems' gene pools.	Kinds of works.	ACE's omic pools (Annex A-§8).

Table 1: Environmental concerns.
Different environmental concerns that may be exposed by an ecologist (a), an industrial ecologist (b) and a life-support system researcher (c). There is no strict relationship between the three columns, only avenues that could be worth exploring as analogies. For an analysis and a deeper description of the mentioned high-level topics as key concepts for ACE analysis in the perspective of scientific and industrial ecology, references to the associated chapters of this manuscript are given in column (c).
First two columns adapted after Hermansen (2003), Frontier et al. (2008), Ayres (2004), Nikolic et al. (2007), Nielsen (2007), Wells (2005), van der Voet (2001), Townsend et al. (2002) and Ashton (2009). Note that first column also describes the main content of a contemporary ecology textbook.

(a) The main concern of the ecologist (biosphere)	**(b) The main concern of the industrial ecologist (techno/econosphere)**	**(c) The main concern of the life support system researcher (ACE)**
Individuals, populations and communities dynamics Growth and regulation, fitness; ecological succession; r and K strategies; carrying capacity; abundance and distribution.	Economic growth, technological improvements and solutions.	Discussed in §3.8 Optimised (accelerated) loop closure; fine-tuning of regulation loops, adjusted carrying capacity; early warning detection.
Evolutionary ecology Ecosystem (co-)evolution, natural selection, selection pressure; stability; resilience; adaptation/mutation.	Economic market pressure applied to processes, and products; law restrictions, environmental policy, company image, business opportunities; discovery, invention and innovation; capitalist competition at the company level.	Discussed in §3.8 ACE co-evolution, human-driven selection and regulation, resilience Long-term monitoring of highly controlled systems.
Species migration, turnover, extinction.	Industry turnover; change of dominant industrial sectors.	Unplanned migration to newly opened areas is forbidden, turnover and human-driven extinction in case of substitution/replacement of an ACE feature by another species.
Man integration in the biosphere Conservation and adaptive management of nature. Species and community integration	Adaptive management, ecotoxicology.	Discussed in §13 CH, autarchic habitat, self-sufficient habitat, off-grid habitat.

Table 1 (continued): Environmental concerns.

Table 2 adapts the translation of natural phenomena into ecological or industrial systems initially described by Wells (2005), and further applies it to the translation from ecological examples into ACE.

In particular, the last aspect highlighted in Table 2 concerns cooperation and synergy which are commonplace for natural ecosystem and, as a design requirement, fostered in ACE and will be discussed in Section 3.3 on artificially predefined symbioses in circular systems.

In addition, symbiosis is at the core of a classical example of industrial ecosystem, that is, the eco-industrial park (EIP). In industrial ecology, the conceptual model of an EIP is based upon ecological relationships (Liwarska-Bizukojc et al. 2009). EIP are defined as a community of manufacturing and service businesses seeking enhanced environmental and economic performance through collaboration (collective benefit) in managing environmental and resource issues including energy, water, materials, infrastructure and natural habitats. An EIP is a showcase of how to incorporate an life-cycle approach for industrial and socio-economic activities and how to integrate it in urban planning and management. An international survey on eco-innovation parks initiated by the Swiss Federal Office for the Environment (2014) described European and international EIP implementing eco-innovation (technologies, processes and services) or industrial symbiosis.

Ecological concept	**(a) Ecological examples**	**(b) Possible translation into ACE**
Alien species invasion	*Many (mostly human-induced).*	Strictly not allowed. Inappropriate ACE species inserted would result in chaos and possible system demise or extinction.
Monocultures do not exist or are highly vulnerable	*In natural systems, even where there are dominant species there is also usually other species ready to fill the space should the dominant species fall. Human induced biological monocultures can collapse rapidly.*	Highly controlled system often based on axenic conditions in microbioreactor and plant monoculture for growth optimisation. If conditions where there is a limited field of uncontrolled competition - like for ACE - are inherently unstable, collapse is prevented by human-induced organisms selection at the initial design level and as species shall be replaced or substituted by any other specie.
Keystone species	*Many ecosystems have a keystone species around which many other life forms are grouped and which define local diversity.*	ACE have a set of dominant species that are rigorously compartmentalised.
Rapid and erratic population change	*Some populations change in established and regular cycles. Others move in counter-cycle. Others are erratic and essentially unpredictable.*	Contrary to industrial systems, a purpose and value of ACE is to show a pattern based on imposed levels of output that systematically considers resource limitedness in order to prevent problems (e.g. an oversupply somewhere in the ACE would in turn generates turbulence elsewhere).
Local adaptation by species to their environmental conditions	*Combinations of climate, soil, topography, etc. all result in a wide range of environmental conditions to which species become more or less adapted.*	The selection of ACE species and their growth optimisation imply that the environmental conditions should be adapted accordingly. In case of local environmental change, species can present temporarily a margin of accommodation.
No species has a 'right' to life	*Any life-form can become extinct, for a wide range of reasons. In the very long-term, few life forms have remained entirely unchanged; most have died out.*	ACE adaptability relies precisely to its capacity to choose which species has the 'right' to be integrated into the system. ACE have to find a balance to be achieved between fitting into a particular set of circumstances (niche) and the ability to transcend those circumstances.
Life extinguishment	*While individual life forms (including people) may ultimately die out, life in general has remained extremely tenacious. Even where a locality has been destroyed, new life forms invade from outside*	ACE organisms can be 'manually' removed for different reasons (generally for system maintenance or performance optimisation). ACE structures can be rebuilt after catastrophic collapse, though it may also take some time once a subsystem needs to be restarted from scratch.
Speciation is as much an environmental process as natural selection	*Forces for speciation are such that, over time, single life-forms can give rise to many different life forms. This could be seen as a process of natural innovation that yields new species able to fit better into available niche conditions.*	The combination of elimination of alternatives (competitors), compartmentalisation and real time monitoring are regulating the process of change, so it is not just about survival of the fittest. There could be a link to innovation here by simplifying and miniaturising the cycling process between species.

Table 2: Ecological concepts.
Natural phenomena and associated ecological examples (a) as described by Wells (2005) for discussing their translation to industrial systems, and here applied specifically to ACE (b). Text in italic is extracted from Wells reference source table.

Ecological concept	(a) Ecological examples	(b) Possible translation into ACE
Biodiversity is the normal condition	*Biodiversity has two aspects: that across the world there are a great many different habitats supporting a great many different species; and that within a particular habitat there might be a large number of species. In both cases, diversity is seen as essential for stability.*	ACE diversity is related to scale, so there will not be such a high level of diversity due to their usual limited size.
Hybridisation and sexual reproduction produce new varieties with new qualities	*Inbreeding usually degenerates populations, especially higher mammals. Interbreeding introduces more variety, some variants may be better adapted to succeed.*	Inbreeding, and even cloning, is human-induced for several compartment species, at least initially (e.g. plant culture chambers). Reproduction is sometimes bypassed by replacing harvested crops by new seedling coming from seed storage.
Waste is the basis of life	*The reproduction of the oak tree is hugely wasteful, with millions of acorns for only a few plants. However, this waste forms the basis for a great many life forms that depend upon acorn production. An extreme example is yeast, which is killed by its own waste products.*	In ACE, where wastes are continuously re-used such that there is no 'waste' that could not be valorised somehow. Thus, in such context, waste reduction becomes clearly irrelevant, except for micropollutant or toxic compounds.
Cooperation and synergy are commonplace	Benefical intra- or interspecific association between species, deriving for instance into an increased carrying capacity. Obligatory mutualistic relationship between organism is defined as symbiosis. Cooperation and synergy make species more adaptive to environment that they would not have been able to tolerate alone.	With ACE, the relationship is characterised by a total synergy, symbiosis fostered by real-time fine regulation by human not only of the environmental conditions (exposome) but also the organisms composition of the ACE. Synergy between compartment is a design requirement from ACE specifications (see §3.3).

Table 2 (continued): Ecological concepts.

Table 3 analyses the similarities and differences between EIP and ACE for the following attributes: goal, social responsibility, science, technological solutions, engineering philosophy, management philosophy scale economic model, role of living ecosystems and industrial relationship, material / chemical flow, water management, waste management, air pollution prevention, biodiversity, energy efficiency, renewable energy sources, mobility, transportation, land use, environmental management systems, cultural and social aspects, health and safety. From EIP initiatives, we can learn how to close the materials loop more efficiently by thinking on a larger scale about the flow back into industry of materials that would otherwise be discarded into the environment. In the perspective of CH[49], we can assess and evaluate to what extent it is possible to miniaturise ACE while maximising the loop closure for material flows by using the approaches listed in

Table 3, which also refers to the respective sections of Oïkosmos Report that cover the associated attribute.

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[49] Cf §13.

Attribute	**Eco-industrial park**	**Artificial closed ecosystem**
Goal	Improvement of the efficiency of material and energy resource use through the economic activities.	Simplification and miniaturisation of ecosystems composed of a limited human population and specific species operating in closed loop. Support for human life (including for its survival in extreme conditions in terms of confinement and isolation) with selected species extracted from nature and integrated by humans in circular systems.
Science	Integrative, holistic. Industrial ecology, material flow analysis.	Integrative, holistic, systems ecology, circular systems Industrial ecology, omics sciences, ICT, closed and sustainable habitat[50].
Technological solutions	Human designs analogous to living ecosystems	Both human designs analogous to living ecosystems and complete integration of elements of living ecosystems.
Engineering philosophy	Single by-product exchange pattern or network of exchanges – the industrial symbiosis. Sharing of infrastructures or services.	Bioinspiration[51], human-designed ecosystems. Integration of ecosystem self-design into final artificial design. Monitoring and fine regulation of organisms' health and environmental conditions (exposome)[52].
Management psychology	Information exchange and facilitation of project implementation.	Management of interdisciplinarity[53] in highly confined environment. Psychosology in closed habitat[54].
Scale	Industrial zone to regional level.	CH[55] to large sealed biosphere[56].
Economic model	Circular economy. Waste valorisation. Mutualisation of supply or treatment for infrastructure or services.	Circular economy[57]. Start-up and industry-oriented. Eco-innovation[58] and tech transfer oriented.
Role of living ecosystems	Analogy, marginal.	Vital for human survival.
Industrial relationship	Industrial symbiosis.	Human designed symbioses[59] at whole circular system level.
Material / Chemical flow	Synergies, exchange of materials (chemicals, waste, etc.) among companies, inter-firm collaborations. Input-output scheme as theoretically defined by industrial symbiosis.	Synergies, exchange of materials (nutrients, organic wastes) among compartments[60]. Integrated input-output scheme as per stoichiometric models, simulation toolkit and mass balance[61].
Water management	Onsite wastewater treatment, reduction/optimisation of water use for infrastructure and production.	Complete onsite/decentralised wastewater treatment and valorisation[62], including nutrient recovery and potable water production from grey, yellow and black water flows, as well as air revitalisation.
Waste management	Onsite collection, transport, onsite or external processing and recycling or disposal of waste.	Onsite collection, processing, recycling and valorisation of waste[63]. Very limited onsite disposal of waste.

Table 3: Similarities and differences between EIP and ACE.
EIP column is adapted and extended from Massard et al. (Massard et al. 2014).

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[50] Cf §5 and Figure 16.
[51] Cf Annex A-§1.1.3.
[52] Cf §7.3.
[53] Cf Annex A-§16.
[54] Cf Annex A-§9.4.3.
[55] Cf §13.
[56] Cf §4.2.1Annex A-§4.2.
[57] Cf §14.4.
[58] Cf Annex A-§14 (competence center), Annex A-§15 (incubator) and Annex A-§18 (open innovation).
[59] Cf §3.3.
[60] Cf §3.3 (interactions) and §3.4 (cycling).
[61] Cf Annex A-§7.2.
[62] Cf Annex A-§7.4.2.
[63] Cf Annex A-§7.4.2.

Air pollution prevention	Reduction in pollutant emissions through cleaner production processes or implementation of end-of-pipe technologies.	Indoor air quality management (including microbial quality)[64].
Biodiversity	Biodiversity conservation or revitalisation of ecosystems in the industrial/urban and surrounding area.	Low to intermediate. Buffering capacities of ecosystems is sized for specific chemical and biological diversities[65].
Energy efficiency	Optimisation or reduction of energy use, including energy needed for buildings and other infrastructure as well as for industrial production.	Optimization or reduction of energy use usually not prioritary, as the main focus is on material loop closure[66]. Dematerialisation.
Renewable energy sources	Use of and/or onsite production of renewable energy. This includes solar energy, wind energy, hydropower, combined heat and power, energy production based on waste, geothermal energy, tidal/wave generated energy, biofuels.	Expected use of and/or onsite production of renewable energy. Energy generation might include in-situ resource utilisation (semi-closed systems)[67].
Mobility, transportation	Efficient viable transport of goods or person with low environmental impact (e.g. public transport, electric vehicles, plug-in hybrids, carpooling systems).	Limited or absence of transport of goods or person after habitat closure. Some possible extra-vehicular activities.
Land use	Optimisation/reduction of land use for industrial/urban infrastructure, revitalisation of derelict land.	Optimisation/reduction of land use for the CH. Possible ACE integration in existing infrastructure.
Environmental management systems	Certification and labels with environmental standards at the park scale such as ISO 14'000 or EMAS.	Standard on CH specifications[68].
Cultural and social aspects	Cultural aspects include the preservation of cultural diversities and valorisation of local specificities. Social aspects include gender equity, professional reintegration, childcare, integration of disabled persons.	Cultural aspects include behaviour in isolated and highly confined environments. Social aspects include ethical dimension [69] and psychosociology[70] in extreme environments.
Health and safety	Health and safety aspects include a safe and clean natural and working environment in the industrial/urban and surrounding area.	Because of ACE size and circular nature, dilution and energy dissipation are small, so the risk exposure is higher in CH, hence the need to ensure healthy habitat features[71].

Table 3 (continued): Similarities and differences between EIP and ACE.

After having positioned the ACE in the context of scientific and industrial ecology and in order to further apprehend ACE at the conceptual level, defining the essential principles of systems (§3.2) represents a logical next step. Thereafter, ACE specific features in terms of interactions (§3.3), cycling (§3.4), biodiversity (§3.5), compartmentalisation (§3.6), reproduction (§3.7) and evolution (§3.8) will be presented and envisaged as key concepts for ACE analysis in the perspective of the research domain of IE.

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[64] Cf Annex A-§10.5.

[65] Cf §3.5.

[66] Cf Annex A-§10.4.

[67] Cf Cf Annex A-§7.4.4.

[68] Cf Annex H.

[69] Cf Annex A-§10.6

[70] Cf Annex A-§9.4.4.

[71] Cf Annex A-§10.5.

3.2 Essential principles of systems to better apprehend ACE

The perception of ecosystems and society as complex systems is widely accepted (Korhonen, 2004a), but the term ‘system’ is sometimes used in a very vague and poorly defined manner. A system is a set of interacting or interdependent entities, real or abstract, forming an integrated whole within boundaries that form its limits with the surrounding environment. An open system usually interacts with some entities in their environment, whereas a closed system is isolated from its environment, at least for a certain period of time. Systems are characterised by processes that transform inputs into outputs, the latter being produced by the consumption of the first. A subsystem is a set of elements composing a system itself, that is a part of a larger system.

Ecosystems are complex, adaptive and evolving as the main goals of the living systems that they encompass are reproduction, mutation and evolution. In that sense, a living system is defined as an autopoetic system, meaning it produces and reproduces its own elements as well as its own structures (Luhmann 2012, p.32). Nature presents several autocontrol mechanisms. In any biological systems such as organisms, ecosystems, or the biosphere, most parameters must stay under control within a narrow range around a certain optimal level under certain environmental conditions. The deviation of the optimal value of the controlled parameter can result from the changes in internal and external environments. The value of the parameter to maintain is recorded by a reception system and conveyed to a regulation module via an information channel.

Feedback describes the situation when output from – or information about the result of – an event or phenomenon in the past will influence the same event/phenomenon in the present or future. When an event is part of a chain of cause-and-effect that forms a circuit or loop, then the event is said to ‘feed back’ into itself. In other words, a feedback loop is a mechanism, process or signal that is looped back to control a system within itself. A negative feedback loop is one that tends to slow down a process, while the positive feedback loop tends to accelerate it. Negative feedback helps to maintain stability in a system in spite of external changes. It is related to balance maintenance and homoeostasis. Positive feedback amplifies possibilities of divergences (evolution, change of goals). It is the condition to change, evolution, growth and gives the system the ability to access new points of equilibrium. In nature, almost all elements participate in feedback and control of the system. Some examples include:

- In biology, the growth of a population is a function of its size and the available nutrients. Growth is controlled not by the total of resources available, but by the scarcest resource. The process can be characterised most simply as a positive feedback loop with a resource constraint.
- In ecosystems, any self-regulating natural process involves feedback and/or is prone to hunting. Ecosystems are dominated by negative interactions and always attempt to return to their optimal functional state. For instance, preys seem to be controlled by predators, but the predators, in turn, are controlled by the availability of preys, which represent the two-side bottom-up versus top-down control of ecosystems;
- In endocrinology, systems such as hypothalamo-pituitary-adrenal and ovarian or testicular axis are largely controlled by positive and negative feedbacks;
- Feedback is also central to gene regulatory networks, both through positive loops (as in the case of the coupling between a sugar molecule and the proteins that import sugar into a bacterial cell) or negative ones (as is often the case in metabolic consumption);
- In enzymology, feedback serves as regulation of activity of an enzyme by its direct product(s) or downstream metabolite(s) in the metabolic pathway;
- The climate system is characterised by strong feedback loops between processes that affect the state of the atmosphere, ocean, and land such as for instance the ice-albedo positive feedback loop whereby melting snow exposes more dark ground that in return absorb more heat thus accelerating the snow melt.

Odum pointed out that self-regulating mechanisms to homoeostasis are the ‘invisible wires’ or the ‘hormone of ecosystems’ as built into natural ecosystems to maintain balance and stability, dynamics and evolution, as well as resilience and resistance (E. P. Odum 1971). However, nature never does anything intentionally (Ehrenfeld 2007). It just changes as conditions change. And it changes in unpredictable ways, moving, if sufficiently perturbed, from one quasi-stable, interrelated set of behavioural patterns to another. Changes in local conditions will also be reflected in the changes taking place within the ecosystem (Wells & Darby 2006). Controls and feedbacks may happen on small scale (daily basis), but biological evolution depends on the variation of genetic material and it usually takes many generations of organisms until a new species is formed (Ring 1997).

Ecosystems are cybernetic systems with internal, diffused/distributed control (Patten 1978; Patten 1998). In short, nature works in absence of centralised planning with self-organising principles (Jacobs 2001). General systems concepts of self-organisation is an alternation between slow production, growth and succession followed by a pulse of consumption, descent. Many assume that the only way down is to crash and restart (H. T. Odum & E. C. Odum 2006). But many systems program orderly descent and decline that is followed later by growth and succession again. Mature biological systems tend to be highly organized and integrated, but decentralised (Allenby & Cooper 1994). The absence in the biosphere of human-like planning and organisation is the cause of the very slow changing processes and long evolution times. IE can take advantage of knowledge about the functioning and regulation mechanisms of ecosystems, based on the language of cybernetics developed over the past fifty years by theoretical ecology so that eventually, knowledge of regulatory mechanisms of both biological and industrial ecosystems could become a strategic knowledge (Erkman 2004).

Contrary to typical ecosystem behavior, where mature ecosystems are self-designing and self-assembling systems (Jorgensen & Mitsch 1989), design and adaptation of ACE is mainly – if not strictly – human-driven, and their development is not following the classical natural selection principle nor the genetic time frame. Nonetheless, ACE like any natural or industrial ecosystem adapt through information feedback and controls. More specifically, control functions are internal and diffuse rather than external and specified.

Successful systems develop structures that maximise useful resource production and consumption, also by feeding back matter and information. This general design is found in biochemical and physiological reactions, as well as in ecosystems and it logically appears to apply to ACE, where individual physiological and nutritional requirements are carefully monitored in real time while on a larger scale the whole crew is participating transversally in the self-organisation of the ACE for maximising performance minute-by-minute. Ultimately, the finiteness of resources provides in ACE one negative feedback loop, while the finiteness of demand provides another, thus helping to stabilise the system.

ACE information flows are stored through various mechanisms. Contrarily to natural ecosystem where such mechanisms involve spore or seed formation, ACE dynamics are designed to be as much as possible predictable, and a constant learning process done by monitoring systems consolidates empirically the knowledge of the ACE behaviour in various context. This inherited quantity of information forms the system memory.

Interestingly, the systemic approach described by Joël de Rosnay (1977) applies particularly well to ACE: ACE connect and focus on interactions between elements and consider the effects of interactions; ACE rely on global perception; ACE change groups of variables simultaneously; ACE integrate duration and irreversibility; validation of facts is achieved by comparing the functioning of the model with reality; it is based on knowledge of the goals, fuzzy details; ACE lead to multidisciplinary teaching.

When considered as bio-cybernetic life support systems, ACE main objective is to provide with human-engineered cybernetics devices a dynamic steady state that is depending on the LSS needs, themselves based on R&D scenarios. The notions of equilibrium, homoeostasis and cycle are central for ACE, as they allow for the integration of the externalities of human crew on its environment and for the sustainable preservation of the foundations of the LSS they form. ACE function on a balance between the desired resource abundance (according to the LSS needs) and species selection to achieve this abundance.

In ACE, species can be abruptly added or removed to efficiently achieve or maintain the desired abundance, unlike in natural ecosystems where communities change more slowly, in response to environmental conditions or disturbances. Moreover, ACE species' role can be driven by changes of parameters or disturbances.

ACE's metabolism relies both on metabolism at organism and system levels. This is intimately related to the industrial metabolism projection to a network of industrial organism defined earlier[72]. As a matter of fact, the study of metabolic interactions represents a crucial challenge to circularise the material flows generated by each of ACE organisms. Such circularisation is discussed in §3.4 and is essential to interconnect the various biological components of the whole system and thus maximise the overall system efficiency.

In this respect, the inclusion of the tools of systems biology applied to the study of the ACE, make it possible to apprehend the metabolomics of its organisms. Metabolomics is defined as the systematic study of the chemical fingerprints left by specific cellular processes, from food to exposure to contaminants in the air. It includes techniques for analysing all the metabolites present in a sample (cellular, tissue, blood and other body fluids like urine and saliva) in order to obtain a detailed profile of their identity, state, activity and location (Wahli & Constantin 2011). The 'metabolome' of a given organism consists of all the metabolites produced by biochemical reactions at a specific time in a particular tissue or body fluid. It includes exogenous (ingested, inspired, absorbed) or endogenous (synthesised) molecules and their derivatives.

Annex A-§8.2.6 examines ACE from the perspective of its global metabolome and analysis of the potential of this theme for developing opportunities for the study of interactions at the interfaces between its organisms, and between its environment. The next section is dedicated to the types of biological interactions found in ecosystems and more particularly in ACE.

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[72] Cf §2.2.2.2 and §2.2.2.3.

3.3 Interactions: artificially predefined symbioses in circular systems[73]

Nature comprises interconnected ecosystems, not isolated subsystems (Straskraba 1993), so that ecosystems are considered to be coupled with other ones. In addition, ecologists usually argue that everything is linked to everything else within an ecosystem (Jorgensen & Mitsch 1989).

In ecology, biological interactions are the relationships between organisms in an ecosystem. These interactions can be categorised into many different classes based either on the effects or on the mechanism of the interaction. Interactions between two species vary greatly in strength and duration, as certain encounter once in a generation (pollination) or live totally within another (endosymbiosis). Effects range from one organism eating the other through predation, to mutualism, as demonstrated below.

At the cellular level, communication and coordination among independent, individual cells preceded the emergence of multicelled organisms. But even for single-cell organisms, closedness has an influence with capacity for microbes to regulate their growth through quorum sensing, a way to detect and respond to cellular density levels (Straskraba, 1993).

A large number of populations interacting through regulation loops and depending on self-regulation ensures the stability of natural ecosystems (Suomalainen 2012). Ecosystems form networks of interacting agents that are quantitatively dominated by indirect interactions. Indirect interactions should be considered as more important to the global ecosystem stability than direct ones, because direct interactions are often buffered by feedback loops (proximal feedback). Indirect interactions are delayed but sustained over time, and influence the system permanently (Patten 1978; Patten 1998).

Table 4 lists some of the main types of interactions between living partners, with the respective cases for biological systems and ACE. For what concerns biological systems, it is important to note that these interactions are not always static. In many cases, two species will interact differently under different conditions. This is particularly true in, but not limited to, cases where species have multiple, drastically different life stages.

Historically, mutualism was often ignored by ecology textbooks the same way symbiosis has initially been by industry. In other words, a disproportionate amount of space devoted to the different interactions, predation and competition are highlighted as important organising principles, while examples of mutualism (such as cleaning symbioses) are presented as interesting but eccentric exceptions to the general rule (Risch & Boucher 1976). Warder C. Allee (1932) was one of the pioneers in regarding 'an automatic mutual interdependence' as a fundamental trait of living matter. Later, Goldsmith (1988) formulated an assumption that a behaviour that 'serves' the interests of the whole must at the same time 'serve' the interests of the differentiated parts, assumption which would apply to all natural systems within the hierarchy of the biosphere. He considered that to a wider extent, the most fundamental relationship between the constituents of the biosphere must be one of mutualism. He argued further that if this were not so, then there could be no viable whole. Consequently, the parts of Gaïa[74], as a single natural system capable of maintaining its homoeostasis, have to co-operate with each other. The opportunistic nature of ecosystems, along with the absence of centralised planning, means that species or individual plants and animals, often have competing needs (Levine 2000).

In industrial system, there is often a trend to condensate and centralise companies, by extinction, due to competition or assimilation of one company into another. More and more capital and labour are concentrated, in fewer companies and products. They seem to be systems that move towards exclusion

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[73] Industrial symbiosis is widely discussed in §3.1, in Annex B1-§7.2 of BELiSSIMA Phase A TN118.1.4, and in Annex A-§6.3 of Oïkosmos Report .

[74] Cf §2.1.

and reduction in number of compartments until perfect monopolies are achieved. In addition to competition, neutralism is also very common for industrial ecosystems and refers to two enterprises living side by side without interference. Even if this situation is generally acceptable and can inevitably persist even within an EIP under establishment, it should lead to the progressive transformation, as much as possible, of the neutral relationship into symbiotic interactions between the actors, often leveraged by third-party organisation playing a facilitating role in such process. On the other hand, many businesses organisational forms have elements of cooperation and synergy, including alliances, joint ventures, research consortia, standards agreements, buyer-supplier relationships (Wells 2005).

As described earlier[75], close industrial complexes in which the individual enterprises interchange their wastes and by-products with others are forming together industrial symbiosis. According to Côté et al. (Côté et al. 1996), one needs to distinguish two kinds of industrial symbiosis: obligatory and facultative. In natural systems, symbiosis is obligatory, which means that if one of the partners is lacking the other cannot survive. This is not the case for the industrial systems, so that we should better call this kind of industrial interaction 'industrial mutualism'. Indeed, obligatory symbiosis is a rare case in the industrial ecosystem as the industrial metabolism of two different types of enterprises is seldom coupled inseparably. The situation is completely different for ACE, as the setup of mandatory relationships for interconnecting ALSS functions clearly aims at ensuring the sustainable operations of the entire system, as demonstrated in Table 4b.

Industrial systems constitute a very recent subsystem of the biosphere, and ACE present a hybrid form of natural and industrial systems, which control interactions between the anthropic material flows and intrinsic nutrient cycles happening at small scale compared to biogeochemical ones by cycling waste within artificial food webs.

ACE imply artificial integration and interfacing of organisms, working together in a synergistic manner at the global level. In particular, interactions in existing material cycles are reduced to their strict minimum and the dimensioning and control of the various compartments allows their operation to be optimised according to defined objectives.

In the ideal situation positive interactions between the ACE organisms should dominate the other ones. Although symbiotic relationships are desired for an ACE, their related conceptual model should consider all three main types of interactions: positive, neutral and negative to properly reflect the relationships existing in nature as described in Table 4a. Indeed, ACE present multifaceted interactions, and show at once several characteristics: the relationship between species can become not only complementary and synergistic as most often, but also sometimes competing and antagonistic. Table 4b also describes and discusses the case for ACE associated to all types of interactions.

Ecotones are formed at the transition zones between ecosystems, and the latter are usually the most vulnerable at these geographical edges (Mitsch & Jorgensen 2003). ACE organisms are usually never directly interfaced as in natural systems as direct contact between non-human species are most of the time restricted to the point that only output flows are connecting organisms between each other. So ACE module's organisms are almost at the direct interface of its inlets and outlets, that corresponds to a transition zone and a type of uniform ecotone over a period of stability. Still, the composition of the intermodular flows may vary over time depending on changes of ACE parameters. This transition clearly represents a point a weakness if these flows are not optimised as per ACE sizing and design. At the same time, these direct connections between ACE modules makes it possible to finely regulate what gets in and out of each compartment, hence increasing ACE's overall robustness.

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[75] Cf §2.2.1 and §3.1.

Type of biological interactions (x/y, effect on X and Y)	
(a) Case for biological systems	**(b) Case for ACE**
Neutralism (0/0)	
Relationship between two species that do interact but do not affect each other.	Not use for key ACE functions, except for ornamental purposes. ACE species are most often isolated from each other, except if a direct interaction is necessary for the optimal loop closure and waste valorisation.
Antagonism, amensalism (-/0)	
Antagonism: a species actively disadvantages another, often through a change in the environment.	In general, to be strictly avoided in the ACE design, and subject to mitigation procedure through countermeasures. If such kind of interaction unintentionally develops, species compartment is restarted or replaced. Fine regulation of material flows and environmental conditions shall prevent a negative interaction to disturb the operations of the circular system and make it start oscillating from its equilibrium. Consequently, such diversion might lead to a potential collapse of one subsystem and up to the entire ACE if no proper countermeasure can be put in place sufficiently early after disturbance. Special case could occur on purpose, where one or few of the organisms in place would also be playing an antagonistic role for other unwished species development, for instance in a relaxing 'habitable' garden whose main function is ornamental or recreative, but not limited to that[76]. One could even consider the use of a plant product for antimicrobial purposes as a form of indirect antagonistic use.
Amensalism: involves one species restricting the success of the other without being affected positively or negatively by the presence of the other (organism Y secretes a chemical that kills organism X).	
Commensalism (+/0)	
Only one of the two associated species benefits from the interaction, with the other usually unaware of the relationship.	Widely present with ACE, notably due to its circularity. Typically taking the form of indirect interactions via the presence of one or several intermediary interfacing modules between the outlet of the organisms in compartment X and the inlet of the one of compartment Y.
Predation, parasitism (+/-)	
Predation is an interaction between organisms in which one organism captures biomass from another. Contrarily to commensalism, parasitism is dangerous to the host.	With exception to humans that implement a controlled predation on several ACE (but showing no prey-predator dynamic pattern as humans are omnivore), otherwise both types of interactions are in principle not welcome in ACE. In addition, most small size ACE do not contain other animal species for sanitary purpose and volume optimisation.
Competition (-/-)	
Competition is an interaction between individuals or populations that are mutually detrimental. Limited supply of at least one biotic or abiotic resource (such as food, water, and territory) used by both is required. Species less suited to compete for resources should either adapt or die out, by natural selection.	Interspecific competition is generally strictly prevented in the ACE design (for instance through crop selection). If such interactions unintentionally develop, for instance within an axenic microbioreactor, it is subject to countermeasures such as species compartment restart or replacement. Intraspecific competition can happen especially for microbial organisms (for biotic resource such as food) or plants (for abiotic resource such as light). Intrinsically, natural selection is lessened notably as organisms are generally initially showing a near genomic pattern due to the upstream strain human-driven selection process.

Table 4: Type of biological interactions
Associated cases of biological interactions for biological systems (a) and ACE (b). Relationships are listed by the effect they have on each partner: '0' is no effect, '-" is detrimental, and '+' is beneficial.

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[76] Cf §13.2.1.5

Type of biological interactions (x/y, effect on X and Y)	
(a) Case for biological systems	**(b) Case for ACE**
Mutualism (+/+)	
Facultative beneficial association between two species, deriving for instance into an increased carrying capacity. Similar interactions within a species are known as cooperation.	Human-driven facilitation in favour of a beneficial association being between two species artificially interacting. *See also Symbiosis case for ACE below.*
Symbiosis (+/+)	
Obligatory mutualistic relationship between organism, living in direct contact. Symbiosis let the sharing of beneficial adaptations for the related organisms, making them more adaptive to environment that they would not have been able to tolerate alone, with the drawback of being dependent to the associated one.	Taken without their back-up loop, ACE loops becomes symbiotic at several periods of their operations. Nevertheless, human-driven ACE community adjustments can make the obligatory mutualistic relationship temporary. As a result of the activity of the ACE, there are the desired products (e.g. food and materials) representing value for their inhabitants, as well as by-products that should be used as an input material for another step in the process within the recycling of matter. Another way of apprehending symbiosis in ACE loop as mandatory is that the global setup of relationships for interconnecting ACE functions clearly aims to ensure the sustainable operations of the entire system. Hence it is to be highlighted that second beneficial relationship from Y to X (the first being the effect on X to Y through a feeding flow) is sometimes indirect when there is no direct feedback loop between Y and X, and happens through the circularity of the standalone system. When no back-up system is put in place to replace one organism function, the system risks to progressively divert from its equilibrium up to a collapsing mode, the speed of this process being regulated by the buffer levels in place (e.g. storage capacity).

Table 4 (continued): Type of biological interactions.

De Rosnay (1995) considered that the relationship between human and technology goes beyond a simple form of co-evolution, and is rather a kind of symbiosis. Contrary to transhumanists advocating the use of sciences and techniques for improving the human being (e.g. the notion of augmented human (Fiévet 2012)), ACE developers seek to foster a form of symbiosis between man and its habitat, consisting in an artful integration of humans into a miniaturised biosphere strongly technicised. At the level of the living organisms of the habitat, the symbiosis is obligatory as at some points all the ACE organisms are mutually vulnerable and rely on the other to live correctly, and usually survive, within the mission constraints (e.g. duration of closure, targeted level of closure).

Now that the interactions perspective for ACE has been introduced, the next key concept for assessing ACE becomes the interconnections in series of its inner interactions to make ACE form a truly circular system. In this respect, the next section envisages cycling and loop closure as a key requirement for developing ACE.

3.4 Cycling: maximisation of loop closure as a critical requirement for ACE

Organisms permanently take in material resources from the environment and excrete them to the environment. Ecosystems tend to keep most vital nutrients within the system based on the efficient interaction between the habitat and its populations (Ring 1997). Over long periods of time and without any major disturbances from outside the system, ecosystems develop material cycles so that in mature natural ecosystems, most of matter is generally cycled to a level close to 100% (Benyus, 2002), with the exclusion of a few important cases[77]. Material cycles tend to be closed locally, on relatively small geographic scales. Obviously, recycling organisms still keep connected to global cycles such as the one of carbon and oxygen for what concerns their gaseous form, as well as the water cycle. But most of the biomass recycling in natural ecosystems (e.g. of dead matter) happens in a more local way, with microbes, plants, and animals all playing niche roles in the process.

If nature suggests that the potential for inventive uses of easily recycled materials is huge (Unruh 2008), it is clear that the vast majority of the times, the economic system do not perform recycling operations as efficiently as do natural ecosystems (Ayres 2004). By contrast, most economic systems are still characterised by a throughput mentality with industrial material cycles that are most of the time widely opened. To simplify, resources are used to produce goods. After consumption, most material goods are still dumped as garbage instead of being reused. In other words, whereas detritus are very important in ecosystems nutrient recycling, and their consumption are critical to the health of the ecosystem, the equivalent functions in human industrial systems were, at least until recently, often regarded only as problems in many environmental policies and industry debates.

Furthermore, in industrial systems, each production stage along the supply chain generally provides products that can be incorporated at the next higher stage. In other words, industrial production capitalises on the added value that is incorporated into products. In a real sense, it is this lack of added value that defines industrial waste. By contrast, added value is somehow more limited in biological systems because of the nature of the digestion process. Much of the structure imparted to biomass by life's processes is lost as a matter of course, and therefore is not highly valued; however, added value is not entirely absent (Levine 2003). When an herbivore eats a plant, it converts some of that plant biomass into animal biomass, a structural change adding greatly to its value to a carnivore. Some parts of the herbivore are more valued by the carnivore. That animal biomass inedible to the carnivore constitutes, at least for that carnivore, waste. Initially, humans, made use only of the edible parts of plants and animals. Then the inedible parts became resources, as humans learned to use wood, bones, shells, horns, and hides (Desrochers 2000). This utilisation of previously untapped resources, and ultimately their conversion to products, represent the early signs of human creation of an industrial system (Levine 2003).

Biological organisms share a common biochemical basis; almost any organism's macromolecules can be broken down into micromolecules so that almost all biological production is available for ecosystem recycling. Predators, scavengers, and decomposers are in fact 'designed' to process organic material. By contrast, products are designed and made of the materials best suited for their functions. Historically, too little attention has been paid to reuse or recycle as one of those functions (Levine 2000). In the IE perspective, a dump is nothing but an artificial mine (Erkman 2004). Unlike recycling in organisms and ecosystems, industrial recycling usually degrade materials. Consequentially, it is not enough to simply seek the recovery of materials, but also the conservation of their properties during recycling, because the degraded materials are not desirable. Down-cycling, destroys the original value, as when a plastic computer casing is melted into a speed bump (Erkman 2004).

The above-mentioned context pushed cycling to become one of the issues widely researched within the

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[77] Cf §2.2.2.1.

field of clean production and IE. The analogy between input–output flows in economics and in ecological systems was one of the first topics to be exploited in ecological economics (Hannon 1973). Since the beginning of the 1990s, the mindset started shifting its view of 'waste' management and recycling activities from a secondary to 'real' economic activity. After the seminal paper from Frosh and Gallopoulos (1989), the awareness that ecosystem principles could be important to study or that industry should use knowledge from ecosystem behaviour has been demonstrated and suggested by several authors such as Allenby and Cooper (1994), Côté et Hall (1995), Erkman (1997) and Hall (2000). In management circles, books on the topics of bioinspiration like 'Biomimicry' (1997), which popularised the concept of innovation inspired by nature, and 'Bioteams' (Thompson 2008), that examined how to draw inspiration and learn lessons from nature's most successful designs for guiding the behaviour of organisational business teams, to cite just a few. Nonetheless, bioinspiration is not simply about 'mimicking nature', which can be misleading: in the IE perspective, humans should certainly get inspiration from the biosphere, and architect a CH compatible with its normal functioning of surrounding ecosystems and above all the ACE it comprises. But this does not necessarily mean designing structures and objects with 'organic shapes', using only 'natural' materials.

Unsurprisingly, to date, few companies have built sustainable manufacturing systems that conform to *most of* the biosphere rules. Fortunately, nowadays, a shift has clearly happened in many industrial sectors as an increasing number of mature industrial communities put in place strategies that 'care' about waste. The way forward still gives many opportunities to further progress into that 'waste as food' mindset so that cycling strategies become more commonly effectively set and implemented.

Recycling and reuse have become essential to achieve sustainability, by shifting from traditional end-of-pipe strategies for manufacturing to alternative integrated and systemic strategies, by increasing resource productivity and dematerialisation. Consequently, the industrial system should be focused on the circular use of natural resources, cascade-like use of energy and so-called closed loops instead of a linear economy with a simple throughput and no valorisation. The linear relationship linking exploitation of virgin resources, production processes, and waste creation thus in theory becomes a circular relationship (Office fédéral de l'environnement 2019), which in turn would be part of an entire circular economy (McKinsey Center for Business Environment, 2015; United Nations Framework Convention on Climate Change 2016)[78]. Therefore, conscientious manufacturers understandably should see planned obsolescence as a vice. If the biosphere does not down-cycle materials, ones should also keep in mind that biological obsolescence – otherwise known as death – plays a vital role in the biosphere. In the context of the implementing biosphere rules, planned obsolescence can become sustainability, leading a company toward environmentally superior designs (Unruh 2008). This analogy perfectly fits with ACE objective of planning the life cycle of its many products, because each compartment outlet becomes the inlet of another one(s).

In the perspective of IE, firms under capitalist competition seek to improve their efficiency in order to survive. In most cases, waste reduction, waste valorisation, as well as material yield rates improvement not only reduce companies' impact on the environment, but also improve their economic efficiency. As said above, IE approach would sometimes even consider to increase the production of a particular 'waste', in the absence of a cleaner production viable alternative, if this allowed this 'waste' to become a marketable by-product (Erkman 1997).

As a reminder, intrinsically, one of the main objectives of IE is to make industrial systems function in a quasi-cyclical mode, just like natural ecosystems[79]. Therefore, among key IE's perceived analogies is the one of the 'life cycle'. All higher organisms exhibit a life cycle, beginning with conception, birth, adolescence, maturity, senescence and finally death. Interestingly enough, similar cycles have been

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[78] Cf §14.

[79] Cf §2.2.

observed for products, firms and even industries (Ayres 2004). Obviously, life cycle analysis approach is one of IE most commonly used tool (together with MFA), is very relevant for studying ACE[80].

In brief, ideally, industrial society should as far as possible come near a quasi-closed ecosystem (Erkman & Besson, 2010; Reddy, Nica, & Wilkes, 2012), and its associated interconnected cycles operating at various spatiotemporal scales and self-maintained by renewable energy.

While loop closure is still rarely found in most industrial ecosystems, it is obviously a critical requirement for ACE design and operation. Contrary to biosphere, which consists of a whole is a set of feedback loops that are partially closed and difficult to distinguish between each other, ACE exhibits more pronounced loop closure due to its specific small-scale and fast operation. Especially on the small scale, an ecosystem can be open with respect to one resource (water, for example) and closed with respect to another (nitrogen, for example). The integration of the various ACE subsystems has to fit form to function in a biomimetic and circular way, following nature's principle of power of shape described by Benyus (2003).

One way in which energy and materials are circulated within an ecosystem is food webs, which extend the food chain concept from a simple linear pathway to a complex network of interactions[81]. Biological ecosystems comprise a set of interconnected food chains describing the eating relationships between species. Many food webs have large numbers of primary producers, fewer consumers, and very few top predators. Omnivores are scarce, decomposers abundant. As discussed above, ecosystems are properly termed 'systems' because energy and materials flow between and among trophic levels. In an ACE, the first trophic level is that of the primary producers (plants), who use energy and basic nutrients to produce biomass usable at the next higher trophic level, either human for edible biomass part, or decomposers (bacteria) for a fraction of the inedible biomass, that receive residues materials. The latter will play a role of extractor to regenerate nutrients from the residues that can flow again to the plant. By transforming waste into environmentally safe materials, decomposer can also neutralise some of the flows of the circular systems. Note than physicochemical processes are also playing an important role in this circularisation of the flow aiming at trending towards integral recycling. Circular system can be considered as an extreme and minimal case of a natural and industrial hybrid ecosystem, where much the fewest possible material resources are lost, thanks to predefined symbiosis, minimal trophic levels, as well as to geographical proximity enhancing for efficient resource use.

In an ACE closed loop, for an effective waste valorisation and resources use optimisation, upcycling processes maintain the value of material flows between the various generated products, side products, and recycled materials without loss of quality or performance. This might involve developing material loops where immobilisation steps occur for certain substances or molecules. But the latter should be captured just temporarily so that no undesirable accumulation process is established within the loop. Such elements or flow components must thus be trapped during certain recycling operations, in order to be further recovered by specific technologies, sometimes in parallel dedicated circuits. The search for upcycling wherever possible leading to quasi-integral recycling is the very signature of ACE. For food production, it means that edible part are valuable for their nutritional characteristic whereas inedible part can be valorised in specific complementary ACE processes: these include the optimisation the feeding of a microbial bioreactor with non-edible biomass, and in some case the non-edible biomass transformation into CO_2 through physicochemical oxidation processes. In particular, recirculating CO_2 into the system is key for several kinds of valorisation processes[82], including for extending the plant production. In the latter case, the reasons may be to increase the food production level and at the same time to provide the capacity to proceed to energy or material valorisation, respectively through

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[80] Cf Annex A-§5.1.3.3 and Annex A-§7.2.5.

[81] Cf §3.3.

[82] Cf Annex A-§7.4.

biorefinery or composting, and through the production of fibres for manufacturing ropes, furniture, walls isolation or structural items, but also to grow plants for ornamental and recreative purposes.

System interactions and cycling being discussed, the next key concept to analyse an ACE in the perspective of IE is its limited diversity, and how it can be compensated by its permanent monitoring, fine regulation and back-up capacities.

3.5 Biodiversity: compensating ACE limited diversity by its permanent monitoring, fine regulation and back-up capacities

Biodiversity is the variation of life forms, from genes to species, within a given ecosystem, biome, or for the entire Earth. Biodiversity is often used as a measure of the health of biological systems. Biodiversity at many scales is critical: the abundance, distribution, and diversity of an ecosystem's structures (species) and functions (such as nutrient cycling) determine its ability to regenerate and reorganise itself and its future pathway. Biodiversity is vital to the normal, healthy functioning of ecosystems because the information it contains and the function it serves constitute the key elements that determine how an ecosystem will self-organise. In other words, biodiversity forms the palette of future possibilities for an ecosystem (Lister 2006). Thus, nature can bank on diversity (Benyus 2003) and retain all kinds of structures (Straskraba 1993). For instance, ecosystem long-term survival strategy relies on various forms of diversity: in species, in organisms, in interdependency, in 'cooperation' and in information. Consequently, this allows high flexibility and adaptability, in permanently changing environmental conditions.

If biodiversity is often essential for stability, system diversity and system stability are nonetheless not always correlated. A low diversity cannot be maintained without external intervention, whether anthropic or due to an external factor (Allenby & Cooper 1994). More specifically, key species are irreplaceable and their disappearance causes a reorganisation of the system, or regression to a less organized system, whereas redundant species are more or less interchangeable, the dominance of one or the other being related to the circumstances and the system history.

Biochemical diversity is the diversity of chemical components of a certain type (such as plant pigment chlorophyll, or saturated or unsaturated fatty acids...). It encompasses not only the diversity within the biomass but also of those excreted and secreted into the media (air, soil, water) as by-products of the increasing community metabolism. As ecological succession progresses[83], extra organic metabolites probably serve increasingly important functions as regulators which stabilise the growth and composition of the ecosystem (E. P. Odum 1969). Chemical and biological diversities contribute to the buffering capacities of ecosystems (Jorgensen & Mitsch 1989).

Paradoxaly, despite its rich molecular diversity, out of the more than one hundred elements, nature chose to use massively just a few. So nature uses a parsimonious palette (Unruh 2008). This is consistent with Aristotle's notion that 'the more perfect a nature is, the fewer means it requires for its operation.' Today we would simply say 'less is more' in that perspective. But the mineral materials are less diverse in comparison with organic one. Nonetheless, there are only 20 different amino acids, common to all life forms, forming a carbon-based materials technology for protein-based natural functions, products or structures. The common chemical constitution of all species facilitates their ability to reuse and recycle basic materials, and by extension most organisms, and allows the grand cycles in ecosystems, such as those for carbon, nitrogen, and phosphorous, to exist (Levine 2003). In addition, no living organism produces a polymer that cannot be broken down by a naturally occurring enzyme (Commoner 1997).

The industrial system, at the opposite, uses more than a hundred thousand of synthesised or natural products, the great majority of them with almost no data on environmental impact on biosphere (and also on health). The diverse materials technologies of industrial production decrease the importance of cycles in industrial systems, as the materials of one technology are often unusable by another. Recyclers often need to specialise in one material. This makes the kind of broad-based recycling done by detritivores in ecosystems less likely to occur in industrial ecosystems. Even within a single product, use

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[83] Cf §3.8.2.

of a great range of materials makes recycling difficult. Thus avoiding multiple materials where possible is seen as a goal of IE (Graedel & Allenby 1994).

In terms of business players diversity, the general attitude is that 'the best competitor is a dead competitor'. In most cases, the goal is simplification of the systems by eradicating competitors until a full multinational monopoly is realised. As a result most of the time, society and industry seem to strive at reducing diversity (for instance, the numbers of farms, dairies, breweries, or grocery chains, the number of varieties of apples) during last decades (Wells & Darby 2006).

ACE development requires considerable knowledge to achieve material loop closure. A striking example is (bio)chemical diversity of closed system, as most bioprocesses depend on inorganic and trace elements. Together, the latter cover a vast part of the periodic table of Mendeleev. Thus, without their high level of characterisation and correct integration with an ACE, the system might collapse at some point. For instance, the local bioaccumulation of an element implies its depletion somewhere else in the system[84]. Clearly, the biodiversity of organic molecules within ACE is significant and can be monitored and regulated with the tools of omics[85].

As a reminder, at the level of ACE organisms composition, meso-scale ACE typically present minimal associations of organisms in symbiosis and eliminate all unnecessary life forms[86]. Even though they present a rather low biodiversity in species, ACE are not showing a high vulnerability thanks to the permanent monitoring – mostly in real time, as well as to the fine regulation and control of its health and environmental conditions. Countermeasures for coping with unforeseen system disturbance such as contamination or disease outbreaks can be ultimately mitigated by using back-up technology for system function replacement (redundancy of technology) or regeneration (bioreactor restart). This pattern makes ACE both robust and resilient.

In any case, it is to be highlighted that up to several hundreds bacterial species are usually present in the human intestinal flora (Qin et al. 2010), which should be considered as the main source of species biodiversity within the system, which composition will influence the downstream compartments in case of organic waste bioprocessing (e.g. through a microbioreactor).

Finally, it is to be noted that ACE innovation value chain is involving a growing diversity in actors (large manufacturers, SMEs, waste management companies, consumers) implying diversity of values, interests and preferences, as well as a diversity in interdependency, cooperation and finally a diversity in information[87].

The next key concept to be explored for ACE analysis is 'compartmentalisation'. This feature is crucial for distributing precisely the role of ACE organisms and their respective operational function.

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[84] Cf Annex A-§7.3.

[85] Cf Annex A-§8.

[86] Cf §3.3.

[87] Cf Annex A-Part III.

3.6 Compartmentalisation: human-driven modular distribution of ACE organisms

Compartments are an important part of the issue of complexity. Compartmentalisation is especially key to the existence of life. In biosphere, terrestrial ecosystems are particularly arranged in spatial compartments, hierarchically organized and forming collections of environments (Patten 1978; Patten 1998). Ecosystems are fundamentally structured in space-time that can be characterised by spatial heterogeneity, temporal variability and interfaces. Space divides ecosystem according to a hierarchical mosaic of interactive parts. Time serves as a framework for flows and dynamics, but also acts by periodic alternations and transitions, all having functional values. Space and time are involved in the movement of organisms or inert material (Frontier 1999).

The size of an ecosystem is crucial for its operation. A small ecosystem is never a model of a large one because organisms detect the spatiotemporal variation of the environment. In a large system such as an ecosystem, the evolution process can manifest itself at different scales forming a set of nested structures, hence the commonly used hierarchical descriptor. According to Holling (2001), hierarchies are defined not in the sense of a top-down sequence of authoritative control. Rather, they should be seen as an aggregation of semi-autonomous levels that are formed from the interactions among a set of variables that share similar speeds. Each level communicates a small set of information or quantity of material to the next higher level. As long as the transfer from one level to the other is maintained, the interactions within the levels themselves can be transformed, or the variables changed, without the whole system losing its integrity. Natural hierarchies are predominantly self-organized, and range from atoms and molecules to organisms and to communities of organisms in inclusive embedded systems (see Table 5a). Socioeconomic and industrial systems also show this type of hierarchical structure (see Table 5bc).

(a) Biosphere	**(b) Socioeconomic system**	**(c) Industrial system**
Biosphere / Earth system / Gaïa	World	
Biome	Europe	
Ecosystem	Country	
Community	County	
Guild	Region	
Population	Agglomeration	Eco-industrial park
Organism	City	Company / factory
Organ	City zone	Company department
Tissue	City quarter	Production line
Cell	Building	Process
Organelle		
Macromolecules (protein, triglyceride, glycogen)		
Micromolecules (aminoacid, fatty acid, glucose)		
Atoms (carbon, hydrogen, oxygen, nitrogen)		
Particles (electrons)		

Table 5: Hierarchical views on biosphere, socioeconomic and industrial systems organisation.
The bio-physiological hierarchy can be continued to physicochemical levels. All are presented as normal scalar hierarchies. Interactions are both intralevel or interlevel. Each activity or function will have a direct influence on several scales, for instance enzymatic cascade or energetic supply.

Both ecological and industrial systems develop over time, but so far they have followed different organisational principles with respect to the basic factors such as energy, matter, information, space and time. The types of environmental problems they encountered pose particular difficulties because of the different temporal and spatial characteristics of both kinds of systems. IE offers one of the implementation strategies to cope with those issues. Industrial ecosystems can view resources on a global basis (whereas biological systems generally cannot), can acquire resources on very large spatial scales if the combination of resource attributes and resource cost is satisfactory (Graedel 1996). Markets are eliminating spatial distinctions so that resources can be used from any place in the world and products can be sold all around the world. Through the continuous trend of globalisation, Ring (1997) argued that the 'ability to cross spatial boundaries for economies helps to neglect internal efficiency as far as the local environment is concerned', and that as a consequence, 'the non-regenerational use of local resources and the destruction of natural habitats is more probable as long as there are resources and habitats left in other places'. Graedel (1996) also pointed out that in relation to the above-mentioned hierarchical approach, it is not atypical for industrial ecologists to simultaneously go across time and space scales depending while dealing with a single project, e.g. discussing 5% decreases in the volume of small-product packaging (a topic with short time range and small in space), assessing the mass of materials in landfills (a topic intermediate in both time and space), and estimating the potential for sequestration of carbon dioxide in the oceans (a topic addressing long periods and the broadest of spatial scales). This capacity to jump from a micro- to a macroscopic perspective contradicts the argument of some authors that IE has little to say about either the geographic or the temporal scale of activity except with eco-industrial parks and regional industrial symbiosis (Wells & Darby 2006).

Human ecosystems and natural one are increasingly coupled, as both are influenced by the other. That is, there is neither a truly natural, wholly biological ecosystem, nor a truly unnatural, wholly industrial ecosystem. All ecosystems are combinations of the actions of nature and humanity. Graedel (1996) stated that we are all in a world in which no biological ecosystem is free of human influence and no industrial ecosystem is free of biological influence. At the level of the substance dissipation, it is striking that even in a remote location on the planet, samples of air and water will reveal molecules synthesised only by modern industry, never by nature: the footprints of humanity. Reversely, in a location as intensely human as you can imagine, as an industrial plant, take samples and examine them with a microscope, you will find bacteria, insects, and perhaps plants, small mammals and birds: the footprints of nature. Thus, at present, all ecosystems exhibit anthropogenic effects in some degree. The purely 'natural ecosystem' seems to have somehow become an abstraction (Commoner 1997).

Chemicals on earth are distributed among four major environmental compartments or conceptual spheres: atmosphere, hydrosphere, lithosphere, and biosphere. Flow of matter interconnects all the four spheres. In this conceptual frame, every sphere has a two-way linkage to every other sphere, including itself. If one compartment or linkage changes, all other compartments respond. Since matter cannot be created or destroyed, the question one seeks to answer is the location and chemical form of the substance at a given time (Husar 1994). The mobilisation of matter by biota is by no means restricted to small geographic regions. The periodic burning of forests and savannahs, for example, not only changes the chemical form of matter, but also results in long-range atmospheric transport and deposition. Some of the biologically released chemicals, including carbon, nitrogen, and sulphur, have long atmospheric residence times, resulting in redistribution on a continental and a global scale (Husar 1994).

As in any system, no element can be isolated even conceptually. But contrary to the vast majority of the cases in the natural world, where no organism is autonomous entity isolated from its surroundings, ACE species can be mostly isolated to the surroundings as a whole, and simply connect into a specific feeding channel. For instance, the inputs and operating conditions of axenic microbioreactors being totally customised and controlled make it work in kind of autonomous mode.

In order to avoid dissipative contamination of the biosphere, the use of technology such as hydroponic culture in greenhouses operating in highly controlled conditions can prevent the loss of synthetic fertilisers and pesticides in water, soil and atmosphere. This concept recognises a basic idea of the EI: it may be, in some cases beneficial to isolate, to the extent possible, industrial ecosystem, to minimise its impacts on other natural ecosystems. Advanced LSS for long-term manned missions such as MELiSSA also exemplifies the implementation of such concept, with precise space scales and rigorous boundaries for each of its module[88].

Spatial boundaries favour increases of the internal system efficiency and naturally set limits to growth. There are natural boundaries caused by changing environmental conditions or the kind of self-organisation of the system itself. Contrastingly, ACE boundaries are precisely set to ensure that environmental conditions would not change, at least on one side of the boundary, through human-engineered design. ACE face the challenge of managing its boundaries, as life requires membranes at each of its hierarchical levels in order to regulate exchanges of material and energy flows. Consequently ACE try to shape organisms so that they will respond to the predicted, predefined – usually optimal – environmental conditions in place. Within an ACE, the 'permeability' between each of its embodied modules is managed as much as possible in a controlled way. When an ACE becomes a sealed habitat sometimes for a long-lasting period of closure, this impermeability with the surrounding environment offers advantages but can also become one of its major constraints.

In principle, CH formed by its ACE components present one of the most appropriate time and spatial scales for studying loop closure and key biological topics such as metabolism, cycling and system boundaries to cite a few of them. Such a closed system is composed by specific environmental compartments, with characterised storage capacity and a controlled capability for redistributing matter spatially. The biospheric part of CH is generally not the only component responsible for the almost full-scale recycling of matter, as physicochemical means can also participate in the recycling within an ACE.

While arguing always remains nearly impossible to delimit precisely one ecosystem from another neighbouring one, Bey (2007) addressed the question whether a more judicious strategy would not be trying to isolate industrial systems from their natural environment and to reduce their size. As their closedness precisely isolate them from their environment, ACE are providing an interesting technology platform in this very respect[89].

Ecosystems have developed more and more efficient ways of using locally available resources. Therefore, the ideal spatial scale for most resources recycle loops in a biological ecosystem is small (Graedel 1996). Accordingly, ACEs benefit from their rather miniaturised size – compared to traditional ecosystems – and meso-scale of complexity, both participating to the maximisation of their search for quasi-integral recycling. Close physical proximity of producers, consumers, and recyclers in a natural ecosystem (e.g. plants, animals, and bacteria in a forest) assures that very little energy is required for the physical transport of matter between them. It also facilitates a rapid mutual adjustment in case of a system perturbation. The same applies to ACE.

In ACE, there are still several important differences from traditional ecosystems compartments and scales. For instance, ACE boundaries are clear and not nebulous or fluctuating in time like in most other ecosystems. Upon initial launch of their experimentation campaign, ACE operation permits limited interaction with adjacent ecosystems, whereas natural ecosystems are usually closely interacting and interdependent for productivity, community structure and biodiversity. As an extreme example, spacecraft, as well as space stations and planetary settlement outside of Earth show very limited interaction with the biosphere. Nevertheless, organisms within ACE are dependent on biological and

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[88] Cf §4.3.

[89] Cf Annex A-Part III.

physical processes as other ecosystems do.

In ecology, a habitat is an environmental area that is inhabited by a particular species (see also §13 for further details). It is the natural environment in which an organism lives, or the physical environment that surrounds, influences and is utilised by, a species population. An ecological niche describes how organism and population respond notably to resources distribution (by growing when abundant resources are available) and how it in turn alters those same factors (limiting access to resources by other organisms). The full range of environmental conditions (biological and physical) under which an organism can exist within its ecosystem describes its fundamental niche (Griesemer 1994). As a result of pressure from, and interactions with, other organisms (e.g. superior competitors), species are usually forced to occupy a niche that is narrower than this, and to which they are mostly highly adapted. Griesemer coined this termed the ‘realised niche’. As a result of a human-driven compartmentalisation process, ACE’s organisms are by definition extremely adapted to their defined niche, as design requirements target the highest possible customisation for them. This results in ensuring an optimised subsystem growth and resilience, as well as robust system homoeostasis.

According to the competitive exclusion principle, no two species can occupy the same niche in the same environment for a long time (Hardin 1960). Accordingly, ACEs basically aim at demonstrating the same pattern for competitive exclusion. In biological systems, once a niche is left vacant, other organisms can fill that position. The situation differs in ACE as unoccupied niches are either unintentional, premeditated or strictly to avoid. The first case involves ACE compartment left vacant due to module unforeseen organism replacement or collapse (e.g. disease outbreak). The second case can for instance happen in a plant compartment after the successful harvesting of a species that reached a mature production stage, either for resowing or refilling it with the same species, or for rotating the crop production with substitutive plant, depending on the chosen agricultural and/or nutritional diet strategy. The third case concerns the prevention of any contamination of a CH location that is supposed to be completely sterilised and kept sterile to the most possible extent. It is to be highlighted that (photo)bioreactors usually operate in axenic conditions where the apparition of other species would be detrimental both for the proper subsystem control and potentially at the whole loop level in terms of yield.

Schematically, organisms constituting industrial ecosystems are often seen as a set of single processing step of transformation of inflows into outflows: an industrial organism (IO) converts incoming energy and materials streams to useful products: e.g. – considering only the material level – aluminium tubes, composite material and tyre rubber are combined into a bicycle in a bike factory, or fruit, milk and plastic are used for producing fruit yoghurts. The various processing steps occurring inside these two examples of IO are usually not taken into consideration and are out of the scope of the study. The same could apply for distinct private organisations part of a supply chain in the framework a material flow analysis, where the key focus would be on the flows connecting the industrial organisms from material extraction step to the final product user buying the product. As described earlier[90], ACE organisms share commonalities with both industrial and biological organisms (BO). Like IO in the IE perspective, ACE require monitoring of the flows in circulation including when they pass through the inner compartments of its organisms.

Like BO in natural ecosystems, ACE organisms must be viewed not only as unit process points of their own ecosystem, but as circles including all the bioreactions that they encompass and all the inputs and outputs that flow through them. Such integration of the bioprocesses that composed their inner content – should it be the microalgae cytoplasm or the plant vascular system – is decisive for well apprehending them. This view also offers opportunities to learn about new kind of interactions within or through its BO, opening a new field of study for IE. At the intersections of the material and energy flows, the organisms can be in direct interaction with the elements circulating through the ‘food’ network of the extreme case

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[90] Cf §2.2.2.2.

of industrial ecosystem that ACE represent and materialise. In a way, this opens organisms' inner medium to the system flows and makes it possible to integrate the internal - 'physiological' - environment of biological organisms as a compartment traversed by the flows circulating through the industrial ecosystem. At these interfaces, organisms - whether human, animal, plant or microbial - can be not only crossed by part of the flows in question, but these flows can also be transformed, shared and exchanged. In this perspective, one can argue that IE would benefit from enlarging its concept and practice to embrace the full biosphere spectrum. And this is where ACE can help by studying ecosystem homoeostasis and self-regulating systems not only on an ecosystem level, but also on the molecular, cell, organism level, thanks to omic sciences, microbiology and embedded monitoring systems.

As a logical consequence, the focus while studying ACE no longer resides just onto an analogy with traditional industrial ecosystems, but on the integration of life sciences taken as a whole[91], as well as on information technology to carefully monitor and exploit the data generated[92], consequentially with opportunities for extending current IE methodologies. As a result, the priority becomes to analyse homoeostasis at both at organism and ecosystem levels, in order to measure new combinations of data and assess the potential, relevance and limitations of novel technologies to innovation processes. The Space Urinalysis Module for Innovative Toilet (SUMIT) project illustrates well the interest of implementing such approach, to address the strong interrelation between the needs to accurately monitor crew health while also maximising the material recycling in space advanced LSS: the accurate monitoring of chemicals in crew metabolic wastes is essential not only for knowing the crew health/wellness status, but also for optimising the functionality of the downstream ALSS processes 'feeding' on these wastes[93].

Compartmentalisation also leverages the role distribution and organisation between ACE species. A generalist species is able to thrive in a wide variety of environmental conditions and can make use of a variety of resources (for example, a heterotroph with a varied diet). A specialist species can only thrive in a narrow range of environmental conditions or has a limited diet. In other words, when environmental conditions change, generalists are able to adapt, while specialists tend to fall victim to extinction much more easily. As most organisms do not all fit neatly into either group, there is a continuum from highly specialised to broadly generalist species. Omnivores like humans are usually generalists. The distinction between generalists and specialists is not limited to animals. For example, some plants require a narrow range of temperatures, soil conditions and precipitation to survive while others can tolerate a broader range of conditions. A species with a highly specialised ecological niche is often more effective at competing with other organisms. Usually, human-driven selection of ACE species makes them become specialists after integration. With the exception of humans, the capacity of ACE to have its organisms substituted by another or replaced by other individuals of the same species makes its overall ecosystem strategy more resilient compared to a panel of specialist in a classical natural ecosystem.

Such human-driven distribution of the ACE species features implies to consider ACE organisms as engineers. In a very interesting paper, Jones et al. (1994) discussed organisms as ecosystem engineers. As ecosystem engineers, ACE organisms directly or indirectly modulate the availability of resources to other species, by causing physical state changes in biotic or abiotic materials. In so doing they modify, maintain and create habitats. The direct provision of resources to other species, in the form of living or dead tissues is not engineering. Rather, it is the stuff of most contemporary ecological research, for example plant-herbivore or predator-prey interactions, food web studies and decomposition processes. ACE organisms act as engineers when they modulate the supply of a resource or resources other than themselves. ACE organisms should be considered somehow as forced engineers whose action can

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[91] For an overview of 'omics' sciences see Annex A-§8.

[92] For an overview of new ICT see Annex A-§9.

[93] Cf §9.1.

generate many kinds of indirect impacts, such as empowering CH by transforming its material flows and modulating its abiotic forces.

The next section discusses how reproduction can be envisaged within ACE.

3.7 Reproduction: a biological process not necessarily occurring for ACE organisms

Genetic replication is a mechanism that provides for the possibility of immortality, not of the individual, but of the species. It assures continuity over time in biology; incorporation of species do the same in CH.

Like in the biosphere, ACE species has not always a 'right' to life, as per Margulis (1999) word. Any life-form can become extinct, for a wide range of reasons. In the very long-term, few life forms have remained entirely unchanged; most have died out. Any industrial system needs adaptability. There is a difficult balance to be achieved between 'fit' into a particular set of circumstances (niche) and the ability to transcend the evolution of these circumstances over time.

In contrast to natural ecosystems, the biological process of reproduction is not necessarily occurring for some of the (multicellular) organisms of an ACE. For instance, seed production can be bypassed by the seedling of upon germination of stored seeds. In addition, no flower is in principle needed to ensure pollinisation and thus plant reproduction. So the reproductive success of ACE is not as crucial as in natural ecosystems, at least for plant crops. Above all, it is a highly controlled act within the system.

In essence, ACEs are simplified versions of real natural or industrial ecosystems, making them more easily decipherable. Of course, such miniaturised systems cannot replicate and reconstitute - or only very partially – existing terrestrial biomes in representative miniature, as larger scale systems such as Biosphere 2 aspire for[94]. Compared to the latter, the target of ACE organisms is not to set an equilibrium at global level from the spontaneous adaptation of the diverse species and numerous populations.

Space ACE reduce their biosphere into the most basic biological processes to sustain its functions. This minimalist and simplified communities show a faster reproduction level and higher turnover of organisms.

The next section revisits natural evolutionary principles in the prospect of ACE.

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[94] Cf §4.2.1 and Annex A-§4.2.

3.8 Evolution: revisiting natural evolutionary principles in the context of ACE[95]

The final key concept for ACE analysis in the perspective of IE is evolution. This session aims to revisit natural evolutionary principles in the context of ACE. First the concept of industrial ecosystems circularisation will be presented in §3.8.1. Then, the notions of ecological succession, as well as resilience, adaptive capacity and selection pressure will be introduced, and the way they applied to ACE discussed respectively in §3.8.2 and §3.8.3.

3.8.1 Towards industrial ecosystems circularisation

The work of Thomas Graedel has led to a discussion on the behaviour of industrial ecosystems and how to create circular systems. He considered all natural systems as dynamic structures with flows of matter and energy, globally forming one whole system that only depends on the solar energy radiation continuously reaching the Earth. Graedel (1996) differentiated three types of ecological systems that are described hereafter.

The (nearly) linear system of type I ecosystems in which the flows of matter are independent. By consuming natural resources and producing waste, these systems correspond to postulated primitive biological systems such as might have existed early in Earth's history. At the beginning of life, the potentially usable resources were so large and the amount of life so small that the existence of life forms exerted an impact quite negligible on available resources. In addition, waste could also be produced in an unlimited way.

The quasi-cyclic ecosystem of type II is an intermediate system that consumes some natural resources and produces waste like a linear system, but where some circular structures can already be found. As the early life forms multiplied, external constraints on the unlimited sources and sinks of the type I system began to develop through a process of change driven by scarcity, leading to the development of feedback mechanisms[96] and resource cycling[97]. Type I and II systems refer to the planet as a whole and regards both ecosystem types as sequential. Individual ecosystems, however, may be of either type in any epoch. Especially on the small scale, an ecosystem can be open with respect to one resource (water, for example) and closed with respect to another (nitrogen, for example). A type II system is much more efficient than a type I system. Nevertheless, on a planetary scale their development is clearly not sustainable over the long term because the flows are all in one direction; that is, the system is 'running down'.

A completely closed circular system is described as of type III. To be ultimately sustainable, the global biological ecosystem has evolved over the long term to the point where resources and waste are indistinguishable, because waste to one dimension of the system represents resources to another. In such a type III ecosystem, cyclicity has been completely achieved, except for solar energy[98].

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[95] Related research outputs:

- The case for ecorestructuration applied to ACE is introduced in Annex-A-§7.2;
- ACE demonstrator as a platform for the regulation of the homoeostasis of organisms and their ecosystem is detailed in Annex A-§7.3.4;
- The notion of resilience and adaptive capacity to changing ecosystem conditions is presented in Annex A-§7.3.4.3.

[96] Cf §3.2.

[97] Cf §3.3.

[98] Theoretically, a strictly closed system is physically impossible, since an energy input is required to balance the entropic conversion of energy into unrecoverable heat (Brooks & Wiley 1986). However, if energy from a source such as the sun is considered part of the system, it can be considered closed from the point of view of material flow and therefore self-sufficient, i.e. without external input of non-renewable energy (e.g. fossil or nuclear energy). The more closed the system is (i.e. the higher the recycling rates), the lower the need for replenishment.

Nowadays and as described by Erkman (2004), the knowledge on life evolution on Earth offers interesting perspectives to reflect on the fate of the industrial system. Life has been able to ensure the conditions for its long-term development, through a long succession of ‘inventions’, that should inspire industrial society such as anaerobic and then aerobic fermentation, and finally, photosynthesis. Erkman considered that the analogy between the early life stages on Earth and the functioning of the modern economy is striking: in fact, the vast majority of the current industrial system is less a true ‘system’ but rather a collection of linear flows that ignores the possible relationship that could be set up between each other, similarly to the type I ecosystem discussed above. In particular, the main operation simply consists to extract resources and reject waste and is the source of our environmental problems. To become truly viable, biological ecosystems have evolved to function almost entirely cyclical. Contrary to biochemical reactions, industrial processes use often almost exclusively fossil fuels, which are not regenerated in the system. In this sense, today's industrial ecosystem, resembles the early stages of biological evolution, when the most primitive organisms got their energy from a stock organic molecules accumulated during the prebiotic period. During hundreds of millions of years, the biosphere has produced all the elements necessary for the functioning of a type III ecology previously described. Historically, however, resource use by humans has mimicked the type I unconstrained resource paradigm, and the industrial system is partly and hardly moving from ecosystem type I to II, semi-cyclical, under pressure of some resources depletion (mainly renewable resources such as water and soil), pollutions and legislative or economic factors (for example, the recycling of precious metals). A natural ecosystem that circulates simple and common materials in a self-organised manner during long (geological) time periods, has barely anything in common with our current economic system that is dependent on a rapid throughput of complex, diverse, toxic, and non-degradable products. Graedel (Graedel 1996) further equated organic flows of matter in natural ecosystems, that can all be entirely decomposed, synthesised, and directly and locally utilised, with flows of complex materials in industrial production and consumption, where the vast majority of generated wastes do not possess these three characteristics.

According to Erkman (2004), if we want to formulate the general goal of IE in the perspective of SE, it would be necessary to pursue the transformation of the current industrial ecosystem, regarded as ‘juvenile’, into the stage of ‘mature’ ecosystem. This maturation process refers to one of the basic theories in ecology describing the evolution of ecosystems, the Clements theory of climax (1936) introduced earlier[99]. The term climax (height or peak in latin) here means the final stage, and assumed stable, of the evolution of a natural environment. The theory, even if far from unanimous among ecologists (Nielsen 2007), can notably describe the succession of different ecosystems that we see in disturbed habitats, because of anthropic activities or non-anthropic elements such as volcanic eruptions, and wildfires. For example, from an abandoned agricultural field evolves a prairie, then a brushwood that finally settles in a forest. In reference to this climax theory, Erkman (2004) proposed to call ‘ecorestructuration’ such maturation of the industrial system. This ecorestructuration cover four main scopes: 1) circularising by closing material loops, as well as by valorising wastes and by-products as resources; 2) minimising losses, which means preventing dissipative losses, or minimising their effects on the environment and human health if dispersion cannot be avoided; 3) dematerialising (intensifying) economic activities, applied both at consumer goods and system infrastructure levels; 4) decarbonation of the energetic system. More precisely, the four principles of ecorestructuration can be applied to varying degrees to the following scales: on a macroscopic scale, it entails improving the material and energy efficiency throughout the entire economy, which is the global perspective of the IE; on a mesoscopic scale, it implies mainly to rethink products and manufacturing processes, particularly to

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[99] Cf §2.1.

reduce waste at the level of production units; and on a microscopic scale, it aims at optimising the process at the molecular level, improving the performance of reactions, developing ways of chemical synthesis with the fewest possible steps, and so on.

Through progressive implementation of the such ecorestructuration strategy over time and at various scales, the conversion of all production systems into type III systems would lead to the creation of an eco-industrial system on a global level, and thus, to a more circular and sustainable economic system. Ultimately, the whole system would be powered largely by solar energy, as industrial ecologists observe being the case for natural ecosystems. Thus, the issue of the concept of IE in such context is clearly to foster the transition towards a type III ecosystem as a paramount objective, with the motto that even if we do not reach it, we aim to. Nonetheless, most of the time, we have to treat a global type III system as a quite abstract conception that seems impossible to attain under real-life conditions, unless potentially in the form of an ACE. The latter can be operated within a CH in type III systems conditions over a long period, and can be perceived as a useful starting point and stepping stone to tackle and foster the transition towards a complete type III *industrial* ecosystem, and equivalent of Graedel's type III natural ecosystem.

In conclusion, one of the very interest of ACE is that one can consider at the same time as minimal natural ecosystems, albeit highly artificial, and, precisely because of the latter characteristic, as mini industrial ecosystems. Although the notion of 'bioinspiration', which is at the core of ACE design, does not imply seeking to purely and simply copy the biosphere, ACE nevertheless represent a tremendous opportunity to draw on knowledge of biological ecosystems to determine the transformations likely to make the industrial system compatible with 'normal' biosphere functioning. Ideally, industrial society should thus be as close as possible to Type III ecosystems. The study and development of ACE represents a step (and perhaps eventually a leap) in this direction.

3.8.2 Ecological successions theory applied to ACE

In 1969, in one of the most cited ecology papers on the strategy of ecosystem development, Odum provided an outstanding and well-known understanding of the principles and dynamic r/K model of ecological succession. Ecological succession involves the development of ecosystems, that has, for the author, many parallels in the developmental biology of organisms, and of human society. E. P. Odum (1969) defined ecological succession with the following parameters: *'1) it is an orderly process of community development that is reasonably directional and, therefore, predictable; 2) it results from modification of the physical environment by the community; that is, succession is community-controlled even though the physical environment determines the pattern, the rate of change, and often sets limits as to how far development can go; and 3) it culminates in a stabilised ecosystem in which maximum biomass (or high information content) and symbiotic function between organisms are maintained per unit of available energy flow.'* More concretely, ecological succession is a phenomenon of colonisation of the environment by living organisms over time and is defined as a sequence of linear or cyclic temporal communities (Buttler 2007).

In unstable or unpredictable environments, pioneer or juvenile ecosystems initially develop. Predominant 'wasteful' species referred as r-strategists form simple linear trophic chain systems characterised by considerable throughput of material flow, a low rate of recycling and only few species interacting with each other, apart from the direct competition for resources. Later, and in contrast, mature ecosystems take place with K-strategist species which are characterised by flows of matter and energy proportionately lower, a high rate of recycling of matter, varied and very specific trophic networks; complex interactions between a large number of species, such as parasitism and symbiosis.

Table 6ab compares respective traits characterising both r/K-selected species. To sum up, K-selected species stabilise the density achieved by adapting to the carrying capacity of the environment and by accumulating internal information reflecting the acquisition of an optimal organisation. A constant environment strengthens a K strategy, an aggressive promotes variable r. r- and K-strategists are the two ends of a gradient, between which many intermediate species are present. Briefly, the 'strategy' of succession as a short-term process is basically the same as the 'strategy' of long-term evolutionary development of the biosphere - namely, increased control of, or homoeostasis with, the physical environment in the sense of achieving maximum protection from its perturbations. Incoming energy and nutrients will be used up to an increasing extent for maintenance of the system's complex structures rather than for further physical expansion through production.

Allenby and Cooper (1994) analogised a sustainable economic system with a natural ecosystem which led them to recommend the creation of industrial production systems that resemble mature ecosystems. They claimed economic activity since the industrial revolution is comparable with a rapidly evolving biological community (r-strategy), while a sustainable economic structure will resemble a mature biological community (K-strategy).

Table 6c refers to the application of the ecological succession criteria to an ACE operated within a CH demonstrator. Like r-selected species, ACE species live in a simple and uniform biotope with few interactions between species, high production yield, and are in general able to grow and reproduce rapidly, but have low lifetime. Similarly to K-strategist, ACE-selected species demonstrate a high rate of recycling of matter, cannot change rapidly their environment, have a controlled population with high density dependence. ACE species are most of the time in regulation loops that avoid antagonism resulting in reduced competitions, and rather strive for synergism and facilitation with predefined symbioses, parasitism and other partly negative interactions being avoided by their design (§3.3). Whereas mature natural ecosystems are self-designing systems, ACE components are characterised by their strictly defined optimal size, as well as human-organized spatial heterogeneity, forming an overall ecosystem with synchronised time scales. It is to be noted that ACE-strategists should not be considered as 'strategists' per se, as they were artificially selected and are kept monitored and regulated in real time almost permanently.

ACE-selected species will develop with fast renewal of its biomass in a predictable manner. This will not result from a direct modification of the physical environment by ACE community itself, as development is channelled through artificial components. Such artificial components comprises hardware for setting physical boundaries to the growth of each module (e.g. bioreactor or plant compartment), or device and software for setting and monitoring the conditions of growth specific to each ACE species. As for mature ecosystems, homoeostasis of ACE requires accordance between biological function and chemical composition, and homoeostatic (assimilation) capacity should not be exceeded. CH operations will culminate with a steady-state conditions in which ACE-selected species tend to maximise the biomass per available volume of CH. ACE-selected species also strive towards optimised adaptation level to the available carrying capacity, which is decisive while developing space LSS. ACE community will be characterised by a quasi-complete synergetic relationship between its different kinds of organisms. The food chains of ACE establish a circular system that produces predominantly products and wastes respectively for immediate use and valorisation. Within a CH physical limits, ACE usually prevent the influence form outer environment through sealed and well isolated boundaries[100], except for data monitoring and exploration that can be partly done remotely in a mission control centre. Finally, ACE share the 'strategy' of long-term evolutionary development of the biosphere as they target the homoeostasis with their surrounding (internal) environment in the sense of achieving maximum protection from any perturbations that could appear.

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[100] Cf §3.6.

Ecosystem attributes	**(a) Developmental stages**	**(b) Mature stages**	**(c) ACE operated within a CH demonstrator**
Community energetic (bioenergetics of ecosystem)			
Gross production/ community respiration	Greater or less than 1	Approaches 1	Approaches 1, for quasi-closed systems Greater than 1, for semi-closed systems with compartment extension (e.g. CO_2 net intake through in-situ resource utilisation for progressive increase of plant production surface).
Gross production/standing crop biomass	High	Low	High. Fast renewal of biomass.
Biomass supported/unit energy flow	Low	High	Low to medium, due to hardware and devices energy demand. Most of the time, energy supply level is not a constraint, due to the limited size of the CH and the focus on integral recycling.
Net community production (yield)	High	Low	High (e.g. optimised crop production cycles).
Food chains	Linear, predominantly grazing	Weblike, predominantly detritus	Circular, predominantly products and waste respectively for immediate use and valorisation
Community structure	Generalist	Specialist	Predefined symbioses.
Total organic matter	Small	Large	Maximised (per unit of volume). Customised to fit the crew needs or the exepected level of material valorisation. Ecosystem components presenting optimised space and synchronised time scales.
Inorganic nutrients	Extrabiotic	Intrabiotic	Both intra- and extrabiotic. Crew can influence nutrient composition in inflows when relevant (e.g. for completing a nutrient solution for a module that would lack a specific component after a few cycles, even though bioaccumulation is generally avoided).
Species diversity	Low	High	Low to intermediate.
Biochemical diversity	Low	High	Intermediate to high. Buffering capacities of ecosystems is sized for specific chemical and biological diversities.
Stratification and spatial heterogeneity (pattern diversity)	Poorly organized	Well-organised	Strictly defined optimal size and human-organized spatial heterogeneity, forming an overall ecosystem with synchronised time scales.
Life history			
Niche specialisation	Broad	Narrow	Extremely narrow.
Size of organism	Small	Large	Customisable.
Life cycles	Short, simple	Long, complex	Short to intermediate, except for human and ornamental plants.

Table 6: Application of the ecological succession criteria to an ACE operated within a CH demonstrator. Ecosystem attributes for a) developmental stages for r-selected species in young, pioneering or juvenile ecosystems; b) mature stages for K-selected species in climax ecosystem; and c) human-driven ACE selected species. Ecological succession criteria are adapted from Odum (1969).

Ecosystem attributes	**(a) Developmental stages**	**(b) Mature stages**	**(c) ACE operated within a CH demonstrator**	
Nutrient cycling				
Mineral cycles	Open	Closed	Quasi-closed.	In semi-closed systems, nutrients use can be increased by in-situ resource utilisation of elements and matter. Such net intake from the outside will serve for the further physical expansion of some of the LSS services in order to increase the production of food or biomass for material valorisation (furniture, fabric, rope, structural elements, etc.). Other interactions with the surroundings are allowed but limited to the maximum notably in order to keep ACE homoeostasis at low energy and material cost.
Nutrient exchange rate, between organisms and environment	Rapid	Slow	Nutrient cycling is maximised.	
Role of detritus in nutrient regeneration	Unimportant	Important	Essential for nutrient recovery.	
Selection pressure				
Growth form	For rapid growth	For feedback control	Both.	Selection pressure for ACE-strategists present combines fast growth and feedback mechanisms that conform to their high resilience and buffer capacity, in accordance with their preceding evolution and integration of the lesson learned from their past responses to unexpected changes they were exposed to. Therefore, ACE resistance to external perturbations is maximised but dependent on their capacity to control and finely regulate the system.
Production	Quantity	Quality	Both.	
Overall homoeostasis				
Internal symbiosis	Undeveloped	Developed	Highly developed and interconnected. The high level of internal symbiosis makes it possible to envisage ACE species as units of co-evolution.	
Nutrient conservation	Poor	Good	Maximal. Initial nutrients stock is supposed to be sufficient for ensuring loop closure over defined period.	
Stability (resistance to external perturbations)	Poor	Good	Maximised. It is one of ACE properties to present a degree of interconnectedness between organisms, internal controlling variables and processes. The level of interconnected reflects the degree of resilience and rigidity of the whole system, especially its sensitivity or to perturbation. Unexpected changes will be detected early after emergence, and countermeasures will be immediately implement to mitigate any possible disturbing effect[101].	
Entropy	High	Low	Very low	The traits characterising ACE-selected species imply very low system entropy with very high information generation and storage, for example when omics tools are used for measuring genes, proteins and metabolites compositions and production levels.
Information	Low	High	Very high	

Table 6 (continued): Application of the ecological succession criteria to an ACE operated within a CH demonstrator.

For the relevance of artificial ecological succession in a ground simulator for ACE[102].

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[101] The context of operating mode shifting is discussed in §3.8.3.

[102] Cf Annex A-§7.3.4.2.c.

3.8.3 Resilience, adaptive capacity and selection pressure applied to ACE

Ecosystems are said to be never stable (Frontier 1999). Nature represents a dynamic equilibrium: species appear and disappear, populations are decimated and multiply again. Major disasters lead to new chances on the evolutionary road. Compared to the biosphere which took several billion years of evolution before reaching its present degree of global stability, the case for industrial system shows time frames that have been drastically shortened in most of the cases. So society should adapt much faster and cannot leave changes to time. In addition static is usually preferred to dynamic in many society situations, because it seems to offer risk-free – and even disaster-free – features. In economy nonetheless it is more clearly a moderate to fast – and if possible continuous – growth that humans aspire to maintain. In any cases, even if time frames are ordinarily different, both natural and industrial ecosystem designs have one way or the other to prove themselves in the real world through the survival of the fittest.

As stated by Nielsen (2007), ecosystems are assumed to be selected for the more efficient overall functionality, that is, their ability to meet changes in their environment with only little or almost no internal change. As they were selected over long periods of time, their functionality must represent good and robust strategies. In other words, existing ecosystems are the ones that are the most fitted in terms of functionality. Contrarily to natural ecosystems, the adaptational and selectional pressure happening in ACE is replaced by the controlled environment offered to its organisms. The latter are selected for their capacity to enter into artificial symbiosis with a few other key organisms within a miniaturised ecosystem. The wished elimination of alternatives (competitors) in ACE is only one side of the process of change, it is not anymore just about survival of the fittest. As a consequence, ACE offers stable conditions in routine operations to its organisms, which are much less exposed to Darwinian natural selection. Actually, the Lamarckian model of evolution (acquired characteristics to be passed on to offspring, in direct response to the animals' needs[103]), largely discredited in biology, is very interesting for ACE, as it is in charting product development (Levine 2000). With products, the results of small modifications, tinkering, and so on, certainly are passed on to 'offspring' products if the improvements are affordable for its consumers. Just like products, ACEs can be empirically fully redesigned and their evolution can make jumps not available to biological evolution.

Among the principles of natural selection applied to ACEs, one can note that: natural resources are limited and in known quantities; populations are generally stable in size (e.g. according to a predefined crop rotation plan); parent organisms produce more offspring than is required to replace them (although sometimes a new generation of plants from stored seeds will be regrown); intra- and inter-species competition is present, but is relative and mostly under control. Concerning the variation (especially genetic) of individuals within one of the populations of an ACE, one will not necessarily want the variations to be transmitted from the parents to their offspring. This is not only because variation will influence survival and reproduction rates, but because it is likely to influence their productivity and the nutritional aspects - both quantitatively and qualitatively - essential to the long-term self-sufficiency of ACE. Finally, natural ecosystem individuals do not evolve. Natural selection applies to the genes they contain, implying that populations evolve over generations. In an ACE, there will be anthropogenic pressure for the full ecosystem not to evolve to an unfavourable stage either. This is a major difference from the usual evolution of an ecosystem in which a trait does not evolve for the 'survival of the species' or for the 'good of the species'. Indeed, natural selection does not act at these levels, but acts only on individuals. Adaptation or maintenance of species are indirect consequences of this effect.

In the perspective of scientific ecology, adaptation requires times measurable on the evolutionary scale.

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[103] Thus giraffes were initially thought to develop long necks through generations stretching their necks to reach leaves higher on the tree, which was contradicted by Darwin theory afterwards.

Most human-induced physical stresses are usually too sudden, too violent, or too arrhythmic for adaptation to occur at the ecosystem level, so severe oscillation rather than stability results (E. P. Odum 1969). This does not apply to ACE as their artificialization and human-induced control imply – and require – a fast, if not immediate, adaptation time frame. So whereas natural ecosystem processes may vary over several orders of magnitude (Mitsch & Jorgensen 1989), processes that are reproduced in ACE have characteristic space and time scales that are much less distributed. For instance, if (re)generation times of soil and groundwater sometimes run into hundreds of years in natural ecosystems, mankind can hugely accelerate nutrient and resource recycling loop in ACE up to an ideal temporal scale ranging from hours (water regeneration) to weeks and months (crop production). In the development of an ACE, communities of organisms in place are juxtaposed in a totally guided and controlled manner so as to maintain a standalone system, perpetuated in a kind of unique climax. Initially, when the ACE is commissioned, the successions are progressive. It should also be noted that since its foundational starting point, the time for ACE to reach its climax or maturity state on the order of weeks to months - is substantially shorter than for a natural ecosystem such as a natural grassland (decades), a montain forest (hundreds of years) or an equatorial forest (hundreds to thousands of years).

In principle, ACE shall be maintained extremely stable as a whole for a long period of time in order to provide their continuous and decisive life support services, and their integrity is theoretically not supposed to disappear at any time. If the ecosystem is in dynamic equilibrium, the physiognomy and structure of the communities will not vary significantly because, in a continuous and self-sustaining cycle, species replace themselves. In the event of disturbance (desired or unexpected) of external origin, regressive successions start appearing, for instance if part of the biocenoses in place must be separated. These disturbances, whether gradual or sudden, can disrupt this balance and the stability of the system, leading to more visible changes. Hopefully, in such cases and thanks to its modularity, an ACE can have specific components or compartment restarted or even a species substituted to keep the system sustainable as a whole. As a matter of fact, the short time frame of development of ACE makes them a valuable platform for simulating system disturbance through specific anthropogenic action such as the modification of the environment (pollution), destruction of biomass, overexploitation or the massive arrival of nutrient resources, as the results would be observable in a short-term perspective, with the possibility for immediate countermeasures and restructuring to stabilise it. Even without aggression, development is not always a stabilisation. In short, for ecosystems, diversity, complexity and uncertainty are normal, and we cannot predict exactly how or when ecosystems will change (Lister 2006). This is rather the opposite for ACE, that have to take surprise and unpredictability into consideration and to mitigate any event almost immediately.

Recently developed in France, ecotrons are kinds of artificial biospheres not doted with human habitat but combining macro-meso-microcosm reconfiguring ecology and for environmental conditions simulation in order to test ecosystem adaptability to change and crisis (Granjou & Walker 2016)[104]. ACE isolation from outside environment is a precondition of its ability to simulate and modulate its own internal ambient conditions, such as automated artificial seasons with scalable sunlight intensity and periodicity and pre-programmed patterns of temperature, wind, humidity, precipitation or CO_2 concentrations, allowing to monitor climate change ecosystemic impacts (Granjou & Walker 2016). In this respect, ACE demonstration could prove to be a judicious support for carrying out biogeosciences studies, and in particular those concerning the processes and mechanisms controlling biogeochemical cycles in natural

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[104] As described in their article, ecotrons 'are large instruments designed to produce experimentally valid knowledge through the controlled manipulation of enclosed, simplified ecosystems.'(…) Originally tasked with assessing the effects of biodiversity loss on the productivity and stability of the biosphere, ecotron research is increasingly focused on anthropogenic microbial ecosystems. (…) Energetically open to solar insolation and heat-transfer but closed to material inputs and outflows, ecotrons materialize and offer proof of the 'ecosystem' concept itself. Immunised from the turbulent complexity of the planetary-scale ecosystem outside the system boundary, ecotron chambers contain carefully selected biotic communities of minimal complexity, such that the fundamental 'nature' of ecological processes can be analysed with physico-chemical precision.'

ecosystems.

As above-mentioned, until recently, most ecologists believed that ecosystems follow a linear path of development towards a biologically diverse and stable climax state. But it has been shown by Holling (2001) that this vision is incomplete: while ecosystems do generally develop from simple to more diverse and complex states, they develop along any of many possible paths and states, or even flip suddenly into entirely new states. The ability of natural ecosystems to recover, reorganise, and adapt in the face of regular change, rather than stability, is critical to their survival. It is in this context that biodiversity is vital to ecosystems as a basis of resilience or 'adaptive capacity' (Gunderson & Holling 2001). This adaptive capacity gives the ability of an ecosystem to maintain the basic structure and buffer itself from being pushed into another state, as well as to regenerate itself following a shift or other disturbance.

The notion of a 'complex adaptive system' describes a variety of human and ecological systems in which nested hierarchies of actors self-organise into relationships to utilise resources while maintaining the capacity to resist or adapt to changes that emanate from internal and external conditions (Holling 2001). The Holling (1986) model (see Figure 6) emphasises the patterns of successive changes in adaptive systems that are sequenced as follows: 1) rapid exploitation of resources that are newly available; 2) long, slow conservation of resources and build-up of stored energy, capital, and connectedness; 3) rapid release of existing structures and resources, such as through a disturbance event; and 4) rapid mobilisation of resources that are made available for future colonisation. During the exploitation phase, the system is expected to have high diversity and unconstrained growth and is composed of above-described r-selected species, whereas conservation phase comprises main K-strategists[105].

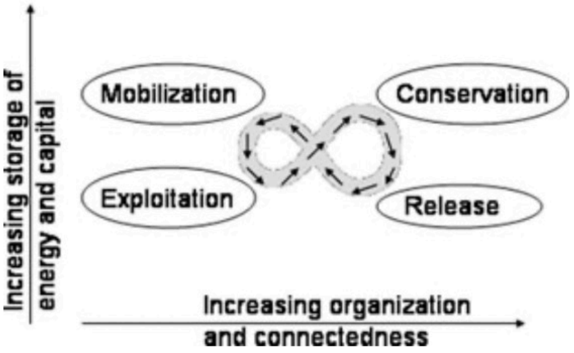

Figure 6: The adaptive cycle in complex systems.
Perturbation during the conservation stages may be expected to cause mobilisation and redistribution of resources and reentry into an exploitation phase. Arrows show direction of succession. Source: Holling (2001) and Ashton (2009).

As discussed earlier[106], perpetuation and sustainability in ACE need adopting a complex system approach. Particularly, complex adaptive systems theory is therefore useful for considering interactions between ACE organisms at multiple levels and examining how those interactions shape and change structure and functions. In ACE, capture and storage of resources leads to conservation stage is characterised by dominance of synergies between compartment. During this phase, connectivity among ACE organisms, as well as material storage and cycling increase within the ecosystem (Figure 6). The high level of connectedness and stored capital can make ACE vulnerable to some disturbances, which

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[105] Cf §3.8.2.

[106] Cf §3.2.

can in turn cause a collapse of one or several of the existing subsystems. This further implies resources mobilisation and ecosystem reorganisation through human-driven countermeasures, and finally reentry into an exploitation phase (e.g. once disturbance appears, it is first mitigated and then ACE organism compartment can be restarted). Such succession in ACE can be brought by internal processes or external events. Nested (ACE) subsystems operate at varying spatial and temporal scales and interact in linear or circular ways which can lead to 'surprise' or emergent effects (Hartvigsen et al. 1998)

In miniaturised ecosystems the maturity state can comprise sometimes compartment maintained in 'pioneer' phase, particularly plant chambers and bioreactors. The ensemble of the compartments shall ensure optimal homoeostasis, self-sufficiency, autonomy and resilience, in a dynamic equilibrium maintained, monitored and regulated by the human-machine interface, with potential periodic fluctuations both exogenous and endogenous. The permanence of an ACE may demand important fluctuations – cyclical or not – of species respective abundances, typically at the level of the crop production for those which grow plants. If so, ACE are characterised by short pulsing cycles. Ecosystems with pulsing patterns are often highly productive. Pulsing prevails when the operations transform more energy than those at steady sate. As environmental conditions change, the response of a system will adapt by optimising, and not necessarily maximising, its efficiency, so that maximum power output can be maintained. In this way, systems tune their thermodynamic performance according to the changing environment (H. T. Odum & E. C. Odum 2006).

Ecosystems have multiple possible operating states and may shift or diverge suddenly from any one of them. The current state of the ecosystem is a function of its physical environment coupled with the accidents of its history and the uniqueness of its local context (Regier & Kay 2002). And so do ACE have the capacity to be shifted in specific operating states and can evolve discontinuously and intermittently. Unlike the natural ecosystems that regenerate to a similar or perhaps different state after a disturbance (Lister 2006), ACE operating modes change depending on the crew needs. In other words, stasis is not the ultimate goal of such system sustainability, but rather resilience and flexibility.

ACE resilience is related to the real-time monitoring and fine regulation done by human crew and algorithm (i.e. bioinformatics) so that contrarily to natural ecosystems, ACE can show a decreased vulnerability to unexpected or unpredictable shocks, surprises or disturbances. If the expectable and the unpredictable will still happen, their frequency and intensity can be much reduced. If ACE can also be envisaged for paving the way towards making ecosystems programmable, it is only possible by adjusting appropriately their sophistication level.

Incontestably, with their capacity to provide life support services in the most efficient ways usually exemplified by their miniaturised size, ACE can be characterised by a complementary relationship between both simplicity and complexity as demonstrated by their operations. This pattern makes them a proper example of 'simplexity' in action, an emerging notion that has been recently coined by Alain Berthoz (2009). In his words, 'making an artificial object *simplex* [is] a complex engineering process of making simple and uncluttered a powerful set of functionalities', a definition which is definitely consistent with features occurring in ACE.

This simplexity process has then to be challenged and adjusted so that ACE mathematical models can predict the whole system behaviour for different set of environmental conditions and scenarios of loop closures. Once initial catalogue of ACE functionalities are leveraged, initial human-driven engineering of ACE can be further consolidated by iteration depending on the effective integration of the lessons learned from previous experimental protocols implementation, in a continuous improvement mindset.

In addition, with their characteristic biodiversity simplification, ACE can be considered as a juvenile stage within the classical ecological succession process discussed above. Nonetheless, an ageing process takes place for ACE as for any ecosystem as they turn more mature and cumulate cycles over time. In return, ACE encounter a pressure for developing into a more mature stage which can generate unbalanced metabolism and make them become more vulnerable to diseases and other perturbations. To reduce the associated risks, their aging is inhibited by the fine regulation of the environmental conditions and the action of replacing any compartment if disturbances go beyond their homoeostasis (i.e. massive influx or lack of a nutritional resource). The same applies for deterioration (i.e. overexploitation) that can lead to a potential recovery. Like for natural ecosystems under persisting disturbance, the high level of regulation keeps ACE in a juvenile state, thus making them unable to evolve. So ACE are sort of maintained in permanent rejuvenation and are well buffered against small aggressions. The persistence of a juvenile ecosystem is accentuated by artificial enrichment of the environment and also linked by a biomass circulation leading to permanent trophic supply. There are loops of material, minerals and water flow through within the system. In a nutshell, strikingly and contrarily to natural ecosystem where mature ecosystem recycle more (especially N and P, the limiting factors of growth), ACE juvenile state is by definition characterised by very high recycling levels.

Revisiting natural evolutionary principles in the prospect of ACE shows that such systems can be operated within a CH in type III systems conditions over a long period, and can be perceived as a useful starting point and stepping stone to tackle and foster the transition towards a complete type III industrial ecosystem.

3.9 Final considerations

Chapter 3 discussed how research on IE can be opened up from its rooted engineering fields, and more particularly how to deepen the scientific knowledge and cross-fertilise the know-how between SE and IE through ACE research. It proposed key concepts for ACE analysis in the perspective of IE, as per RO1.2, and investigated their relevance for consolidating the conceptual foundations of IE. It first positioned ACE in the context of scientific and industrial ecology (§3.1). Next, it provided essential principles of systems for better apprehending ACE (§3.2) notably by introducing the notions of system feedback and control. Later, sections §3.3 to §3.9 explored key concepts for ACE analysis in the perspective of IE. The examined concepts encompassed 'interactions' on artificially predefined symbioses in circular systems (§3.3); 'cycling', envisaging loop closure as a critical requirement for ACE (§3.4); 'biodiversity', for compensating ACE limited diversity by a permanent monitoring, together with a fine regulation and control of its health and environmental conditions (§3.5); 'compartmentalisation', consisting in a human-driven modular distribution of ACE organisms (§3.6); 'reproduction', as a highly controlled biological process not necessarily occurring for all ACE organisms (§3.7); and 'evolution', revisiting natural evolutionary principles in the prospect of ACE (§3.8) by discussing ecosystems circularisation, ecological successions, as well as resilience, adaptive capacity and selection pressure applied to ACE.

Clearly, the scope of these concepts also overlaps and sometimes shows a significant level of intertwinement, such as between 'interactions' and 'cycling' for loop closure elaboration or between 'compartmentalisation', 'biodiversity' and 'interactions' for ecosystem simplification.

As extensively discussed in the Part II of this work, the study of the reviewed key concepts would benefit from the availability of a ACE simulating facility. Chapter §5 and Annex A particularly discuss the opportunities offered by such demonstrator at the interface of terrestrial and space research on ACE, with the following references for each of the above-proposed key concepts:

✧ Interactions:

- deepening of the concepts, strategies, methodologies and tools of IE (Annex A-§7.2): a vector for the development of dynamic material flow analysis (Annex A-§7.2.3);
- an instrument for improving our knowledge on ecosystems (Annex A-§7.3.1): observing interactions at the 'organism-habitat-environment' interfaces (Annex A-§7.3.1.3);
- an experimental platform for biomonitoring the exposome (Annex A-§7.3.3), and in particular the interactions within a closed system between a human crew and its environment;
- the biorefinery of the by-products of ACE (Annex A-§7.4.4);
- the dynamic interactions between organic molecules and cellular components taking place in biological systems (Annex A-§8);
- interaction sciences and human-machine interfaces (Annex A-§9.3.3);
- psychosociology in CH (Annex A-§9.4.3.2).

✧ Cycling:

- deepening of the concepts, strategies, methodologies and tools of IE (Annex A-§7.2): a laboratory for testing, modelling and developing 'industrial' food networks (Annex A-7.2.4); a driving force for improving the assessment of impacts (life cycle assessment methodology) (Annex A-§7.2.5);
- an instrument for improving our knowledge on ecosystems (Annex A-§7.3.1): monitoring of accelerated biogeochemical cycles in near real-time (Annex A-§7.3.1.1);
- a facilty for the decentralised treatment of organic waste (Annex A-§7.4.2);
- an experimental testbed for the chemical and biochemical valorisation of carbon dioxide (Annex A-§7.4.3);

- self-sufficient habitat (Annex A-§10.3).

✧ Biodiversity:

- an instrument for improving our knowledge on ecosystems (Annex A-§7.3.1): exploring and testing the principles of biomimicry in extreme conditions (Annex A-§7.3.1.4);
- enhancing adaptive capacity to changing ecosystem conditions (Annex A-§7.3.4.3): 'massively parallel' architecture (Annex A-§7.3.4.3.c);
- systems biology research within an ACE demonstrator (1/2): from genomics to metabolomics (Annex A-§8.2.6): ACE biomonitoring to apprehend ecosystem molecular biodiversity;
- microbiomics within ACE (Annex A-§8.3.3.3).

✧ Compartmentalisation:

- a driver for the optimisation of microorganisms culture in (photo)bioreactors (Annex A-§7.3.2);
- an instrument for improving our knowledge on ecosystems (Annex A-§7.3.1): observing interactions at the 'organism-habitat-environment' interfaces (Annex A-§7.3.1.3);
- an experimental platform for biomonitoring the exposome (Annex A-§7.3.3), and in particular the near real time monitoring of ACE compartment operations: what enters them, what they contain and store, what goes out;
- hypermonitoring of the exposome (Annex A-§7.3.3.2): analysis of the distribution of microcompounds and chemical contaminants (Annex A-§7.3.3.2.d);
- artificial intestine (Annex A-§8.3.3.4);
- mathematical modeling of the processes of ACE (Annex A-§9.2.1);
- healthy habitat (Annex A-§10.5).

✧ Reproduction:

- homoeostasis of ecosystem (Annex A-§7.3.4.2);
- enhancing adaptive capacity to changing ecosystem conditions (Annex A-§7.3.4.3): 'massively parallel' architecture (Annex A-§7.3.4.3.c);
- the interdependence between the exposome and the biological processes of the ACE (Annex A-§8.2.4).

✧ Evolution:

- an instrument for improving our knowledge on ecosystems (Annex A-§7.3.1): observing interactions at the 'organism-habitat-environment' interfaces (Annex A-§7.3.1.3);
- homoeostasis of ecosystem (Annex A-§7.3.4.2);
- enhancing adaptive capacity to changing ecosystem conditions (Annex A-§7.3.4.3): resilience (Annex A-§7.3.4.3.a);
- microbiomics within ACE (Annex A-§8.3.3.3);
- control of the evolution of microbial communities via systems biology technologies (Annex A-§8.2.4);
- the interdependence between the exposome and the biological processes of the ACE (Annex A-§8.2.4).

The implementation within an ACE simulator of such research, related to the key concepts described in this chapter, would contribute to the operationalisation of IE discussed in Part III, and ultimately lead to the development of self-sufficient habitats on Earth[107].

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[107] Cf §13.

One way to approach the synergistic relationship between the crew and its habitat is the user-building symbiosis[108]. The integration of a miniaturised biosphere such as an ACE into a minimal habitat makes the latter become what can be considered as a ‘unit of living’[109].

The next chapter examines more particularly space ACE or ALSS as a model for industrial ecosystems under extreme constraints (RO1.3).

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[108] Cf §13.3.2.

[109] Cf §13.4.

4 Space ACE as a model for industrial ecosystems under extreme constraints (RO1.3)[110]

Chapter 4 first reviews the key milestones of the space exploration (§4.1). Subsequently, it introduces space ACE, namely space advanced life support systems (ALSS) (§4.2). Finally, it examines space ACE as a model for industrial ecosystems under extreme constraints (§4.3, RO1.3).

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[110] For an overview of the space and terrestrial research synergies on ACE within the framework of the Oïkosmos programme, see §5 and Annex-A-Part II of Oïkosmos Report .

4.1 A brief review of the key milestones of the space exploration

Man has always had a thirst for knowledge, prompting him to explore the boundaries of the world around him. In the twentieth century, man's propensity to experiment with new and exciting adventures has taken him beyond the limits of the Earth. From a dream until the middle of the 20th century, space conquest became a reality with the development of functional rockets, such as German rocket V-2, the first artificial object to travel into space in 1944. Later in 1957, the Soviet Union successfully launched Sputnik 1 into orbit by the R-7 rocket, which was considered to be the beginning of the space era. USSR initiated the same year the first life-carrying flights with the dog Laïka, followed by several other animals and plants with Sputnik 5 flight. In 1961, NASA sent two chimpanzees into orbit, but it was the cosmonaut Yuri Gagarin who inaugurated the first manned orbital flight during the Vostok 1 mission of the same year. These events marked the start of the space race, a period that reached its pinnacle in 1969 with the Apollo-11 mission and the first steps of Neil Armstrong and Buzz Aldrin on the lunar soil.

The firm intention to perpetuate the presence of mankind in space took shape with the construction of Salyut, the first Soviet station in 1971, and Skylab, the American station in 1973. Other followed, such as the Russian MIR station in 1986, as an outpost for long-term space research. In 1998, the International Space Station (ISS) was launched and progressively extended, and more recently the Chinese station Tiangong-2 was put in orbit in 2016. Today, the ISS is the only one still in service. These stations aim at carrying out various scientific and technology missions funded by their respective space agencies. However, as a symbol of international cooperation in space, the ageing ISS is only funded until the mid-2020s (Oberhaus 2020), and its exorbitant global cost (including its decommissioning) became unfavourable to ensure the financing of a new station in low Earth orbit by the member countries of the International Space Exploration Coordination Group (ISECG). In 2015, ESA General Director Jan Woerner notably proposed replacing the ISS in orbit around the Earth with a permanent 'lunar village', a 'concept' open to all. Still the implementation plan of this vision seems not to have really taken shape even at the level of ESA itself, although meanwhile, Trump administration has been pushing for manned mission to the Moon in 2019.

In parallel, the emergence of New Space[111] since the early 2000s showed that the future of space exploration will be increasingly leveraged and developed by private investors and entrepreneurs, with SpaceX as a flagship enterprise. Although a Lunar Gateway (formerly 'Deep Space Gateway'), a future space station in lunar orbit, led by NASA in collaboration with ESA, CSA and JAXA, is expected to be placed by mid 2020s as a relay point for assembly, logistics and refuelling of deep space transport, the ultimate goal for space agencies remains clear: sending a spacecraft for the human exploration of the Martian surface in the 2030s (International Space Exploration Coordination Group 2018).

Such space missions with human crews can be distinguished by their long duration and their remoteness from Earth (Committee on Human Exploration 1997)[112]. These characteristics make them differ profoundly from traditional manned missions carried out to date, which are either of short duration (e.g. Apollo missions to the Moon) or are carried out at close range (e.g. ISS in low Earth orbit). In the first case, the crew can take with them all the elements necessary for survival, and in the second case, it is possible to resupply the crew via refueling at regular intervals during the mission. In both cases, vital elements such as oxygen and food are produced on Earth and stored onboard. Once these vital resources have been consumed, the associated organic waste (carbon dioxide, urine, faeces) is stored after physico-chemical treatment, before finally being brought back to Earth.

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[111] Cf §15.1.

[112] 'In reality, maybe one per cent of an astronaut's career takes place in space, and one per cent of that is done in a pressure suit.' This assertion Mary Roach, best-seller author of 'Packing for Mars: the Curious Science of Life in the Void' (Roach 2010) will be contradicted from once the launch of a crewed mission to Mars. Indeed, both the duration and travelled distance from Earth of such mission are the major paradigm shifts of deep space exploration compared to traditional manned missions.

Consequently, as deep space exploration missions involve keeping human groups far away from Earth for long periods of time, they depend on life support services and require the development of specific systems to ensure crew survival, space ACE or advanced LSS, most of the time composed of partial but that will ultimately be equipped with complete closed-loop systems. Space ACE or advanced LSS are introduced and discussed in section §4.2.

4.2 An introduction to space ACE[113]

4.2.1 A brief note on the historical context of space ACE development

The potential of biological organisms for closed systems in an aerospace context has been studied for decades, for instance with plants for atmosphere vitalisation (Myers 1954) or fishes as an intermediate trophic level between algae and man for bioregeneration (Taub 1963).

Historically, NASA has undertaken research projects aimed at replicating some of Earth's biogeochemical cycles to provide ACE in future space missions by developing 'controlled ecological life support systems' (CELSS) (Karel 1982; MacElroy & Bredt 1984), materially-closed ecosystem (Folsome & Hanson 1986) and miniaturizing simplified agro-ecosystems for advanced life support (Volk 1996; Kliss et al. 2003). The objective was to meet the mass and volume reduction requirements of such missions and focused on:

- agro-ecosystems based on simplified food chains composed of plants (producers), humans (consumers) and micro-organisms (decomposers);
- a design optimising plant crop productivity through high sunlight conditions, hydroponic growing conditions, high carbon dioxide levels, cultivation coupled with genetic selection, as well as in the presence of other controlled environmental factors;
- mathematical modeling to achieve the objectives by establishing trade-offs, analysing the growth and development of experimental crops, and showing how to increase crop yield (harvest index) through modified crop models.

According to MacElroy (1987), 'the concept of CELSS is based on the natural recycling processes that occur in the terrestrial environment'. The aim here is to create an ecosystem that can be exploited by humans and capable of providing life support functions for a crew, by artificially reproducing material cycles similar to those occurring in the Biosphere within small closed systems (Kliss et al. 2003). However, a CELSS cannot be considered directly as an analogue of a terrestrial ecosystem, because its volume and the size of its material reservoirs are tiny, and the rate of renewal of material cycles is much faster given the limited number of compartments and the reduced dimensions of the system[114]. These characteristics require the system to be highly artificial and controlled. The notion of 'smallness'

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[113] Space ACE or advanced life support systems (ALSS) are extensively described in the following sections of the associated research outputs of this study:

- Annex A-§4.1 of Oïkosmos Report on biological or bioregenerative life support systems (BLSS);
- Annex B1 - Swiss Position Paper on ALSS - A brief introduction to space ALSS and their relevance for terrestrial sustainability (Annex 2);
- Annex C2a-§8.2 of BELiSSIMA Phase A TN118.1.4.

MELiSSA project is introduced and detailed in the following sections of the associated research outputs of this study:

- Annex A-§4.2 of Oïkosmos Report on the projects of ESA connected to ACE;
- Annex B1-§1.3 of the Swiss Position Paper on ALSS - Introducing the MELiSSA project and its connection with Swiss organisations.

Terrestrial applications of ALSS are widely discussed in:

- Annex A-§4.2.1.5 of Oïkosmos Report on the project of ESA connected to artificial closed ecosystems (in French);
- Annex A of the Swiss Position Paper on ALSS - Swiss Space and terrestrial ALSS and MELiSSA-related activities (in Annex 2);
- Annex I - Proposal and progress report of SCIMA Connected Autonomous Monitored Greenhouse;
- Annex J - ESA Study for the Assessment of the Financial and Business Potentials of the Life Support Systems (LSS) Technologies (confidential).

Section 4.2.2 partly refers to elements from §2.1 of the proposal submitted by ESTEE SA and CSEM to the Swiss Space Center for the call for proposal 2020 (Mesure de positionnement), namely 'Development of SUMIT (Space Urinalysis Module For Innovative Toilet)' drafted with Dr. Petros Dimitriou-Christidis (§9.1 and Annex D1).

[114] Cf Annex A-§7.3.1.1.

of the system is crucial here, as it implies an efficient use of mass, energy and volume for all space systems.

CELSS can be based on the cultivation of higher plants as a source of food (Turc et al. 1999; Zabel et al. 2016), with the main function of regenerating the atmosphere by producing oxygen from human exhaled carbon dioxide (BIOS 1 and BIOS 2 projects) (Gitelson et al. 2004). In their review of closed ecological systems projects, Nelson et al. (2010) describe such systems as ‘biospheric’ ones.

A CELSS is centered above all on man - i.e. humans are its ‘key species’ (Cristancho & Vining 2004) - as shown by the experiments carried out in the Russian demonstrator BIOS 3 (Gitelson et al. 1976; Gitelson et al. 1989; Salisbury et al. 1997), as well as in the United States started at the end of the 1980s in Biosphere 2 (Allen et al. 2003).

In particular, the Biosphere 2 experimental site was built by Space Biosphere Ventures between 1987 and 1989 to reproduce a large-scale closed ecosystem in the Arizona desert. With a volume of more than 200'000 m^3 on over than two hectares, this huge structure was intended to try to recreate a biosphere in a sealed dome, namely ‘Biosphere 2’, considering the Earth as ‘Biosphere 1’. Two experiments were carried out in the early 1990s by small groups of scientists operating without external supplies during two missions, two years and six months long respectively (Allen et al. 2003). The aim was to create compartments reproducing analogous terrestrial biome environments, in anticipation of future space colonisation. To do this, different continental, aquatic and marine ecosystems were reconstructed (desert, savannah, tropical forest, etc.) (Nelson et al. 1993).

The establishment of such large-scale Biospheres, comprising greenhouses with several dozen plant species (including edible species such as potatoes, rice and bananas) and a few animal species (pollinating insects, pets and food producers: poultry, sheep, etc.), required significant machinery to ensure adequate environmental conditions for the growth of plant crops and animal husbandry. Biosphere 2’s goal of food self-sufficiency required a significant effort from the researchers during the mission, particularly for the operation and maintenance of ecosystems, as well as the preparation, processing and storage of food.

Participants in these experiments have sometimes been criticised for a form of militant ecology or even a lack of scientific rigor. However, while the ecosystems as a whole were probably insufficiently controlled, the overall engineering of the system was generally successful. Biosphere 2 still remains today an indispensable reference for large-scale closed ecosystems, which has allowed to draw rich lessons from them[115]. As per Mark Nelson words: ‘I like to say we built it not because we had the answers. We built it to find out what we didn’t know.’[116]

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[115] Among these useful lessons learned from the Biosphere 2 missions (Eckart 1997; Engel & Odum 1999; Silverstone et al. 2002; Allen et al. 2003; Dempster 2008; Nelson et al. 2009; Nelson et al. 2015):

- air flows are not sufficient to avoid alterations in the quality of the atmosphere. Maintaining the atmospheric composition is much easier with simplified systems combining higher plants and microscopic algae;
- material flows must be controlled and adjusted to the different operational activities;
- the complete recycling of organic waste (human and animal) is achievable by reproducing various natural mechanisms;
- the production of a variety of foods in sufficient quantities in a closed system is possible;
- a very limited number of animal species must be introduced in the first instance;
- the establishment of prey-predator balances is extremely difficult to achieve;
- the soil adds significant complexity. Control of the activity of symbiotic soil microorganisms is crucial. The humus of some natural greenhouse soils, whose microbial flora was not sufficiently monitored, has seen a significant decrease in carbon content, following a faster than expected metabolisation of this element, leading to oxygen consumption and carbon dioxide release;
- a back-up physico-chemical engineering system (back-up system) must be ready to take over in the event of a greenhouse malfunction;
- a global approach is essential, in order to envisage the success of the progressive integration of technical systems and the sustainable operation of such installations;
- these systems must integrate technical and biological components (hybrid LSS).

[116] The Guardian article published on 13.07.2020, ‘Eight go mad in Arizona: how a lockdown experiment went horribly wrong’:

In the following years, Nelson et al. (2013) reviewed the ecological challenges of such closed systems. In particular, experiments carried out there have shown that the difficulties become considerable to overcome as the volumes and biodiversity of the system increase.

The two successive Biosphere 2 missions have been the subject of numerous other publications - some of which are still recent - that are relevant to ACE (Engel & Odum 1999; Allen et al. 2003; Dempster 2008; Nelson et al. 2009). These publications suggest that large-scale analogue biospheres are an opportunity for the study of complex biological phenomena and for the study of interactions between biological and technical systems, which require: a sufficient supply of raw materials and chemical elements; an adequate genetic reserve (strains, seeds, seedlings, seeds, eggs, embryos, etc.) to maintain the desired biodiversity; a highly efficient and sophisticated maintenance and repair system with spare parts manufacturing capacity; a highly reliable computerised engineering and biological control system with a multitude of chemical, physical and biological sensors; in a space context (planetary basis), it is also a question of ensuring sufficient gravity and protecting organisms from ionising radiation.

From 1995, the management of Biosphere 2 was entrusted to Columbia University until 2003, in particular to study the effects of global warming on ecosystems by manipulating CO_2 levels. Today, the site is operated by the University of Arizona and hosts various projects related to this issue[117]. For their part, the biospherians pioneers have continued experiments on life support systems, but on smaller scales (a few hundred square meters of plant cultures) and without integrating humans, for example in the modular Laboratory Biosphere facility in Santa Fe, New Mexico, for educational and research purposes (Nelson et al. 2008).

Beyond the difficulties[118] encountered in the Biosphere 2 experiments, let us note the broader issue related to the ability of humans to recreate ACE on a large scale. One of the challenges is to form complex assemblies that remain sufficiently stable and resilient, due to their capacity for bioregeneration and adaptation to their direct biophysical environment. To develop such large-scale infrastructures, the research effort becomes considerable, as do the financial, intellectual and time resources. Thus, it seems preferable to carry out a certain number of experiments on smaller scales beforehand.

The foreseeable risk of instability of Biosphere 2 could thus explain why NASA has not invested in the project. In fact, space agencies have favoured a more traditional approach which gives priority to systems with simplified biodiversity (Barta & Henninger 1994; Volk 1996) and of a more adequate size to ensure control of extreme conditions, close monitoring of performance – in quasi real time –, and the implementation of countermeasures in the event of major problems which could not be detected early on.

In the perspective of man's development of the future small ‘Biosphere X’ systems, a compromise must be found between the development of oversimplified mini-ecosystems - whose low biodiversity limits resilience in some respects - and that of Biosphere 2 type mega-ecosystems, which are potentially too unstable due to their considerable complexity.

As a matter of fact in the United States, initial efforts have focused mainly on CELSS. The microbiological

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https://www.theguardian.com/film/2020/jul/13/spaceship-earth-arizona-biosphere-2-lockdown.

In the same magazine article, Matt Wolf, director of ‘Spaceship Earth’, of the 2020 Biosphere 2 documentary said ‘[t]he experiment revealed that humans are the most unstable element of a closed system.’

[117] See the official website of Biosphere 2: https://biosphere2.org (last retrieved on 07.07.2020).

[118] Among the main difficulties encountered during the first two experiments were problems of atmospheric and ecological balance (Dempster 2008): the oxygen content sometimes decreased alarmingly: oxygen injections were necessary; CO_2 levels fluctuated significantly: CO_2 absorbing devices were introduced into the chamber; photosynthesis seems to have been insufficient, potentially due to periods of low light levels; some of the CO_2 seems to have been absorbed by the concrete of the structures and slabs; and fluctuations in air composition have led to the disappearance of part of the fauna (mainly vertebrates).

approach seems never to have been seriously considered, despite their usefulness for the treatment of solid and liquid waste (Garland 2007). On the other hand, this path has long been explored in the USSR within the BIOS-3 experimental complex, notably by Joseph Gitelson at the Institute of Biophysics of the Siberian Branch of the Russian Academy of Sciences in Krasnoyarsk (I. I. Gitelson et al. 1976). Later, work has begun in this field in Japan (group of Prof. Keiji Nitta, Institute for Environmental Sciences, Aomoriken, Tokyo) (Nitta 1999) and more recently, the Chinese space community developed testbeds such Lunar Palace 1 (Fu et al. 2016) and its upgrade Lunar Palace 365 (Fu et al. 2021)[119].

In Europe, ACE development started in 1987 notably through the initiative of Frenchmen Claude Chipaux and Daniel Kaplan of MATRA Espace, Max Mergeay (SCK-CEN, Center for the Study of Civil Nuclear Energy) and Willy Verstraete of the University of Ghent. These pioneers initiated the activities (Mergeay et al. 1988) that were to become the ESA below-described MELiSSA program in 1989, of which the ALSS will serve as a reference for this study.

4.2.2 Advanced Life Support Systems (ALSS)

Space habitats pose major challenges (Rapp 2007; Seedhouse 2009b; Moore 2010; Seedhouse 2020), with constraints in terms of:

- reliability: with requirements for maximum autonomy, no escape or emergency exit, no possible return, the need for in-flight diagnostics, monitoring activities for early detection of potential problems, indispensable repair and redundancy strategies ;
- logistics: no possible restocking and necessary reduction of dependence on perishable products;
- size: with maximum reduction of mass and volume and miniaturisation of equipment, notably in order to control mission costs;
- performance: with requirements for losses minimisation, reduced energy consumption, high flexibility, high adaptability, durability.

Not to mention the challenges related to propulsion, shuttle docking, robotics, protection against space radiation, countermeasures against the effects of microgravity, and so on. In a nutshell, space habitats inexorably forces their users for survival, being constantly threatened by risks of biosafety (contamination) and operation failure leading to death.

The above-listed constraints dictate the primary objective of space exploration missions, which is precisely to reduce the onboard mass of metabolic consumables necessary for the survival of the crew. Indeed, given the increased distances and durations, the technical limitations of launchers and the associated launch costs, it becomes impossible to carry on board a spacecraft all the elements necessary for survival, the mass of which is considerable if no recycling of the on-board biomass is planned. In other words, the open systems (i.e. without looping of material and energy flows) used so far for short or unmanned missions are becoming prohibitively expensive. To understand it, just take a hypothetical mission to the Moon with the Russian Energia launcher. According to Dr. Christophe Lasseur, who leads the MELiSSA project[120], the average human consumes about 1 kg of oxygen, 1 kg of food and 3 litres of water daily. On the other side, a crewmember will produce anything between 10 to 20 litres of grey water daily, along with 1.5 litres of 'yellow water' (urine) and 0.2 litres of 'black water' (solid organic and human waste). Rounding these quantities, if there are twenty kilos per person per day for food, water and oxygen should be 7.3 tonnes of 'consumables' goods to allow a crew of four

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[119] Cf §6.1.1.

[120] Cf Annex A-§4.2.3.

astronauts to spend a year on the Moon, more than all of the payload of Energia launcher. Under these conditions, the proposed space missions taking place over several years with many crews seem seriously at risk. It leaves only one solution: to produce oxygen, food and potable water on board, through a maximal recycling of the residues of the crew metabolism and hygienic water. Therefore, as previously demonstrated in §3, the only solution is to take inspiration from the almost cyclical functioning of the Biosphere's ecosystems. This is why the main space agencies (ESA, NASA, JAXA, RSA, CSA) have been developing projects for autonomous bioregenerative systems, integrating precisely such 'bioinspiration' approaches. The more that can be recycled, the less needs to be carried.

In a nutshell, as humans venture in space at increasingly longer distances from Earth and for more extended periods, two needs become pressing: to maximise material recycling in space (spaceships or settlements) so that the dependence on resupply from Earth is minimised (Mankins et al. 2018); and to accurately monitor crew health for better understanding the effects of space travel and colonization on health, as well as devising effective prevention and medical intervention strategies (Hodkinson et al. 2017). While, the two needs may not appear directly related, their strong relation is evident when considered in the framework of the development of space ACE, namely advanced life support systems (ALSS).

ALSS provide the basic functions that sustain crew life and health in a closed-loop fashion: transforming wastes; supplying food; controlling pressure, temperature, and humidity; and providing usable water and breathable air. For a long time, we know how to almost indefinitely recycle air and water in the spacecraft, using physical and chemical techniques. In the long term, food becomes a limiting factor. The organic wastes, broken down by carefully selected microbial strains, would serve as a substrate for the growth of bacteria, unicellular algae, or even higher plants. An example of an ALSS is European Space Agency (ESA) project Micro-Ecological Life Support System Alternative (MELiSSA) (Hendrickx et al. 2006). Its objective is to scale down the terrestrial ecosystem into sizeable dimensions for space exploration. MELiSSA consists of five interconnected compartments. Each compartment is colonized by different organisms and focuses on different functions: compartment I performs liquefaction of organic wastes (crew feces and inedible plant wastes) by anoxygenic acidifying microorganisms; compartment II performs further removal of volatile fatty acids by photoheterotrophic anoxygenic microorganisms; compartment III performs crew urine nitrification by aerobic chemoautotrophic bacteria; compartment IVb performs nutrient uptake by higher plants, used as food by the crew; and compartment V is the crew compartment[121].

Following other manned ACE features[122], MELiSSA's miniaturisation of an ecosystem geomicrobiology is completely anthropocentric and parameterised to accommodate only the influxes and outflows of human bodies with the material loop (Walker & Granjou 2017). Such ACE must also be perfectly compatible with human physiological needs and in particular nutritional requirements, intestinal flora, skin microbiology, to name just a few.

In addition, space ALSS are characterised by (Eckart 1997; Suomalainen 2012): 1) isolation, boundedness, closedness, 2) (relative) simplicity, 3) limited space and weight, 4) high reliability and stable functioning, 5) reduced operating time scale, 6) limited resources and difficult resource replenishment (self-sufficiency necessary), 7) limited carrying capacity and fragile environment, 8) tight link between sustainability and survival. Also, models are required to accurately predict mass and energy balances in ALSS (Boscheri et al. 2012).

More concretely and in simple terms, in an ALSS, the chemical elements in the metabolic wastes of the crew (urine, feces, and respiration) are recovered (either in the gas phase as CO_2 or in the aqueous

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[121] Cf Annex A-§4.2.1.

[122] Cf §3.1 and §4.1.

phase as inorganic ions), then utilised by plants for food production, and finally, utilised by the crew through nutrition (Clauwaert et al. 2017; Pickett et al. 2020). Space compatible microbial strains can be used for some essential bioconversions of the ALSS loop such as for the nitrogen cycle (e.g. Nitrosomans ureae and Nitrobacter winogradskyi), resource recovery from urine (Christiaens et al. 2019) and for photosynthesis and food supplement production through the cultivation of microalgae such as spirulina (*Arthrospira spp.*) (Lindeboom et al. 2018; Ilgrande et al. 2019). It is to be highlighted that NASA established a reference document (Anderson et al. 2018) compiling ALSS baseline values for the vast majority of its key subsystems.

To illustrate the kind of implications of interconnecting ALSS module in a closed-loop fashion, the accurate monitoring of chemical elements – as biomarkers – such as crew metabolic wastes (especially urine[123]), is essential not only for knowing the crew health status, but also for determining the functionality of the downstream LSS processes ‘feeding’ on the crew metabolic wastes.

More specifically and as based on the typical ACE features described in §3.1, an ALSS ensures 1) the supply of water (drinking water and personal hygiene); oxygen and food (essentially vegetal biomass) for the crew, and 2) the recycling, the regeneration and/or the valorisation of organic wastes (faeces, non-edible parts of plants), air (exhaled CO_2) and wastewater (including urine). ALSS recycling activities take place in a highly controlled environment, with immediate time horizon, and focus in particular on carbon, hydrogen, oxygen, nitrogen, sulfur, and phosphorus content, that represent 95% of the recycling matter. Nevertheless, taking into account the numerous trace elements, their study is in reality essential too (§8), as supporting long-term space missions operating in bioregenerative mode requires the use of a wide range of chemicals and reagents products (Gòdia et al. 2002). Particularly, in a space station consumer waste containing faecal material may introduce micropollutants such as heavy metals, hormones, or pharmaceutical drugs (Hendrickx et al. 2006). Like in natural ecosystems, the behaviour and effects of organic micropollutants in an ALSS like MELiSSA are largely unknown. Short cycle times and small buffer volumes make circular ALSS interesting platforms to study (eco)toxicological effects of micropollutants on micro-organisms, plants and food under ‘accelerated’ conditions (Annex C2a).

For a long time, microalgae are known to offer a number of benefits to support long duration manned space exploration (Verseux et al. 2016; Niederwieser et al. 2018; Revellame et al. 2021). When integrated to ALSS and used as a photobioreactor (Fahrion et al. 2021), they can provide nutritional value (high content in proteins, lipids, essential amino acids and vitamins), capacities for organic waste treatment (urine valorisation) (Yang et al. 2008; Sachdeva et al. 2018; Wollmann et al. 2019), as well as for carbon dioxide fixation (Matula & Nabity 2021) and oxygen regeneration through photosynthesis (Poughon et al. 2020; Alemany et al. 2019). Compared to higher plants, microalgae possess higher growth rates and fewer cultivation requirements and generate less waste. Microalgae can also show resistance to harsh environment (Billi et al. 2019; Wang et al. 2021), for instance in terms of extremes in temperature, pH, as well as high salinity.

Most ALSS are composed of plant growth chambers for food production. Indeed, the development of space agriculture has been sustained since the 1960s (Wheeler 2017) and multiple plant biology experiments have been pursued for plant cultivation, selection, and productivity in space, not only for food production purposes, but also for regeneration of waste, as well as recycling of carbon and oxygen (Kordyum & Hasenstein 2021). Sophisticated soil-less cultivation systems (Paradiso et al. 2014), namely hydroponic systems with thoughtful design, foresee different zones for each crops, which help optimizes the environmental parameters (humidity, CO_2, O_2, temperature, etc.)[124]. Stacked-growth systems are utilized to maximise biomass yield and minimise the waste production per unit area. To further reduce the waste production, the inorganic nutrient solutions are constantly recirculated, usually mainly through

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[123] Cf §9.

[124] Cf Annex A-§9.3.

hydroponic nutrient delivery systems. Nonetheless, hydroponic waste streams can be treated in the wastewater treatment units for greywater (Bamsey et al. 2016). Regarding the sizing of the plant growth chambers, the current NASA plant diet is of a 164 m^2 surface when scaled to the current daily metabolic demand of a human (12.7 MJ/CM-d) (Anderson et al. 2018). According to Kaschubek (2021), the minimal area for the exact desired composition of macronutrients (carbohydrates, lipids and proteins) based on a crop optimization algorithm is of 107 m^2 using chard, lettuce, peanut, bell pepper, snap beans and spinach, which can be reduced to 40 m^2 of wheat and white potatoes if a deviation in the macronutrient composition is allowed. For technical reviews of the challenges and opportunities of food production in space environments see Carillo et al. (2020) for physical constraints, light-emitting diodes (LED), candidate crops selection and nutrient delivery systems, as well as De Pascale et al. (2021) for the effects of space factors on plants, the resource use efficiency and microgreens as complement to diet. Also, Paradiso & De Pascale (2021) summed up the most relevant research on higher plants achieved yet in the perspective of their cultivation in an extraterrestrial environment. Accomplishments made and challenges faced by space agriculture offer terrestrial benefits in return (The Space Agriculture Endeavour 2016).

The integration of man in an ALSS loop like MELiSSA within a CH requires beforehand: 1) the demonstration of the closure of the loop with animals, 2) the clarification of the nutritional requirements resulting from the medical and physiological studies in bed-rest carried out in the ISS, 3) the acceptance of consumables and food by the crew and 4) the control of microbial and chemical risks.

Nations like China also integrates animal protein in a three-stage ALSS development strategy (Liu et al. 2021): first stage with water and gas cycling, hydroponic plant cultivation, second with plant cultivation using soil-like substrates from ISRU and inedible biomass cycling used to grow insects such as mealworms, and finally a third stage for larger scale ALSS with inorganic element cycling with salt water production for fish cultivation.

At the level of space ACE, Volponi & Lasseur (2020) gave an overview of ALSS features in the ISS. The authors also pointed out that the present rate of closure of the onboard systems of the ISS is low and incomplete, but regeneration levels are rising thanks to multiple ongoing studies and projects. Moreover various sources of unwanted molecules are produced in a space ACE atmosphere such as the off-gassing from materials (especially plastics), the metabolic by-products, the smell caused by food and its preparation processes, the housekeeping cleaners, all the scientific experiments, etc.

Finally, food production requires more volume, mass and energy compared to the recycling of water and oxygen[125]. Consequently, its large implementation pays off only for very long duration (twenty years near Earth) and/or very distant space missions (several years of permanence on Mars) (Jones 2006).

Crew time requirements for human space exploration missions is as critical as mass, energy, and volume requirements. The current pricing policy rate for commercial activities on the ISS is of $ 130’000 per hour[126], and such costs will most probably get bigger for planetary base activities, hence a need to minimise as much as possible the crew efficiency. To operate plant growth systems, crew time can be reduced with adequate choices of crops, automation, artificial intelligence and virtual assistants, and sufficient crew training (Poulet et al. 2021). Zeidler et al. (2021) investigated how crew time and workload needed to operate space analogue on-site and remotely, in particular to guarantee a reliable and

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[125] As indicated by Volponi & Lasseur (2020, p. 144): ‘Technically, when we speak about ‘life support’, we always mean the very basic elements that are necessary for the human life: oxygen, water, food. This is the case because, for the short space missions humanity has undergone until now (i.e. maximum one-year length), these are the mayor concerns (which make sense: mayor health problems can be excluded via astronauts’ selection and issues as vitamins deficiency takes definitely more time to kill a person than lack of oxygen): but in the case of perpetual sustainability, everything has to be taken into account for effectively sustain the crew alive.’

[126] NASA commercial pricing policy, 2019, edited by Michael Johnson, updated on 25.02.2021: https://www.nasa.gov/leo-economy/commercial-use/pricing-policy (last retrieved on 01.03.2021).

efficient workflow for greenhouse management and remote support capabilities.

To summarise, main ALSS subsystems include collection of organic wastes in the cabin (inedible biomass, human wastes, etc.) and packaging, etc.; collection, stabilisation and treatment of wastewater (yellow, grey, black, vegetal fibres); recovery (C, N, P, oligo-elements), storage, transport and supply of drinking water for the consumption and the personal hygiene of the crew. Other ALSS features found in manned spacecrafts such as the ISS are used to regulate pressure and temperature, relying today mainly on physico-chemical processes and for fire detection and suppression.

Looking at the MELiSSA project, which aims to recycle theoretically everything by using biological, chemical and physical systems, Erkman (2004) drew a few conclusions of the research on space ACE with the prospect of IE. First, although the MELiSSA project has been designed for manned spaceflight, its related long-term terrestrial applications appear very promising. Such ACE could be used to treat organic waste in a decentralised manner, while producing pure water, oxygen and food[127]. Then, for industry, one of the most relevant MELiSSA project outcomes resides in the specific mathematical models that describe the dynamic – sometimes competitive – growth of bacteria, microalgae and plants in different interconnected compartments[128]. The system is quite explicit, which monitors the development of bacterial populations knowingly. These mathematical models have a major interest for industrial biotechnology, mainly to optimise bioreactors management, especially in the case of several coupled bioreactors. One of the most difficult part of the MELiSSA research has been to establish precisely the equations describing the behaviour of different bacterial populations on the basis of multiple tests facing difficult problems of data acquisition. Thus following the adage, to know you have to measure, to understand you have to predict (Ciurans et al. 2022).

In conclusion, further development of space ACE seem desirable for a number of reasons. As shown by Nelson et al. (2013), they represent powerful tools for studying living systems, opening the door to fundamental research on ecosystem functioning and ultimately to the creation of miniaturised biospheres that can be embarked on a space shuttle. In addition, space ALSS represent an interesting poly-functional laboratory for engineering sustainable, quasi-closed-loop systems, functioning in a reliable and stable manner with limited resources, and in a very limited amount of space. Space ALSS typically uses physico-chemical systems and a combination of biological organisms (bacteria, algae, plants, etc.) to regenerate air, water and food with the objective of complete self-sufficiency. It must provide extensive features that are essential and vital for the ecosystem and human survival and also necessary to the fulfilment and achievement of space mission. Microorganisms cultures are employed to recycle water from wastes; higher plants are an essential source of fresh food through cultivation and harvesting, water is also partly recycled through plant evapotranspiration, and oxygen is produced by higher plants or microalgae photosynthesis. Last but not least, ACE are highly desirable to provide Earth-like aspects as a reminder of the home planet.

The goal of ALSS is very ambitious, since the unpredictable dynamics of living communities constitute a serious challenge in terms of deterministic behaviour of the system. These systems are highly non-linear, with a certain level of uncertainty in their behaviour, making it impossible to perform a complete analytical modelling of the processes. It is therefore necessary to develop, in parallel with the biochemical, metabolic and physiological studies, new approaches to system control. Many of the issues identified for ACEs (such as analytics, monitoring, impact assessment, removal of contaminants, etc.), also apply to the circular life support concepts studied and the ALSS developed in the context of long-haul space missions.

Oïkosmos programme describes in detail the convergence of space and terrestrial R&D agenda within

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[127] Cf §14 and Annex A-§7.4.

[128] Cf Annex A-§9.2.1.

a ground simulator for ACE/ALSS demonstration[129]. Such hybrid experimental testbed can also be seen as an unprecedented technological platform dedicated to closed systems[130].

Considering the above paragraphs, ALSS can therefore be envisaged as an excellent focal point for approaching ACE in the perspective of scientific and industrial ecology. The next section examines space ACE/ALSS as a model for industrial ecosystems under extreme constraints.

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[129] Cf §5 and Annex A-Part II.

[130] Cf §6 and Annex A-Part III.

4.3 Space ACE as models for industrial ecosystems under extreme constraints

As highlighted earlier[131], space habitats are characterised by specific challenges in terms of reliability, logistics, weight, performance, safety, etc. The work in the area of ACE originated from survival problems posed by future space missions of long duration as manned planetary exploration missions can not be resupplied, demand maximal autonomy and offer no way out. Space ACE or ALSS are developed to provide the necessary conditions to sustain human life in such hostile environment over prolonged periods of time.

Table 7 summarises the key definitions around the notions of ACE provided in the Part I of this thesis.

Natural ecosystem.	A system of living organisms occupying a habitat, together with those aspects of the physical environment with which they interact. *Source: Adapted from Townsend et al. (2002) and Shorter Oxford English Dictionary*
Industrial ecosystem.	A man-made system that mimics the way nature flows work, analogous in its functioning to a community of biological organisms and their environment, in which the waste from one industrial process can serve as the raw materials for another, thereby reducing the impact of industry on the environment. Industrial ecosystems are themselves particular components of natural ecosystems. *Source: adapted from Frosch & Gallopoulos (1989) and Erkman (2004).*
Artificial Closed Ecosystem (ACE).	A simplified and miniaturised ecosystem operating in closed-loop. It uses biological organisms (bacteria, microalgae, plants, animals, etc.) to regenerate air, water and food with the objective of complete self-sufficiency. As an artificial set-up, an ACE encapsulates and interfaces a selection of engineered pieces of ecosystemic elements. It replicates and shortens some of Earth's biogeochemical cycles, and thus accelerates nutrient and resource recycling loops that occur in the terrestrial environment. ACE organisms fulfil the same role of producers (plants), consumers (animals) and decomposers (microorganisms) as natural ecosystems on Earth. Compared to natural ecosystems, ACE boundaries are clear and not nebulous or fluctuating in time. ACE operations allow limited interactions – if any – with adjacent ecosystems.
Life Support System (LSS).	A 'crewed' ACE – that is an ACE with humans – designed to ensure health, safety and minimal comfort in extreme environments so that humans can survive in autonomy in confined and isolated habitats over prolonged periods of time. The succession of highly-controlled LSS compartments (e.g. bioreactors, plant growth chambers) are combined to meet the human needs and achieve an uninterrupted conversion and regeneration of organic wastes such as exhaled carbon dioxide, urine, feces and non-edible parts of plants into breathable atmosphere, potable water and edible biomass.
Advanced Life Support System (ALSS) or space ACE.	ALSS are required for long-term manned space missions or habitations. As space ACE, ALSS are designed to ensure the required environment for humans to sustain life in outer space habitats over prolonged periods of time; decrease terrestrial resupply requirements of fungible materials (consumables) by regenerating human resources through biological processes; and prevent some form of pollution to extraterrestrial bodies by recycling organic waste. Being highly sophisticated, a space ACE is the ultimate case of an industrial ecosystem.

Table 7: Key definitions around the notion of ACE in the context of this thesis.

Running a complete ALSS implies to recreate an ecosystem ex nihilo, and then to maximise and sustain the health of all its organisms. The proper functioning of a space ACE is totally dependent on a healthy biological ecosystem, both in terms of the micro-organisms and the plants that make it up. In such an ALSS, the system as a whole, i.e. its hardware, the living organisms it contains, as well as the resource stocks at its disposal, represent a completely self-sufficient entity that must not depend on any inflow

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[131] Cf §4.2.2.

from its immediate environment. Consequently, one of the most interesting biotechnology outcomes for IE undoubtedly will come from current research on artificial microbial ecosystems.

As illustrated above[132], industrial ecologists try to reconnect humanity with the natural environment in all sorts of ways, to build bridges between the artificial, controlled human world and the diverse natural world (Haber, 2004). Within the conceptual dimension of IE research, ACE also lie at the crossroads of industrial and natural ecosystems, as depicted in Figure 7. Indeed, the concept of IE is based on an analogy (not an exact correspondence) between the functioning of natural ecosystems and that of the industrial system (§2.2.2). The development of space ACE can be seen as an appropriate and empirical way to further understand and test the validity of this analogy. For instance, a space ALSS can be compared to an ecosystem in which matter and energy are exchanged between the different subsystems that compose it and that interact together (Pechurkin & Shirobokova 2001). This is one of the reasons why this report has chosen to use mainly the terminology of space artificial closed ecosystems (space ACE) throughout the following chapters, since this notion also refers to the possibility to consider both CELSS (Chamberland, Knott, Sager, & Wheeler, 1992) and ALSS (Stasiak, Gidzinski, Jordan, & Dixon, 2012), as a simplified, miniaturised and highly controlled ecosystem, that is, a particular case of an industrial ecosystem.

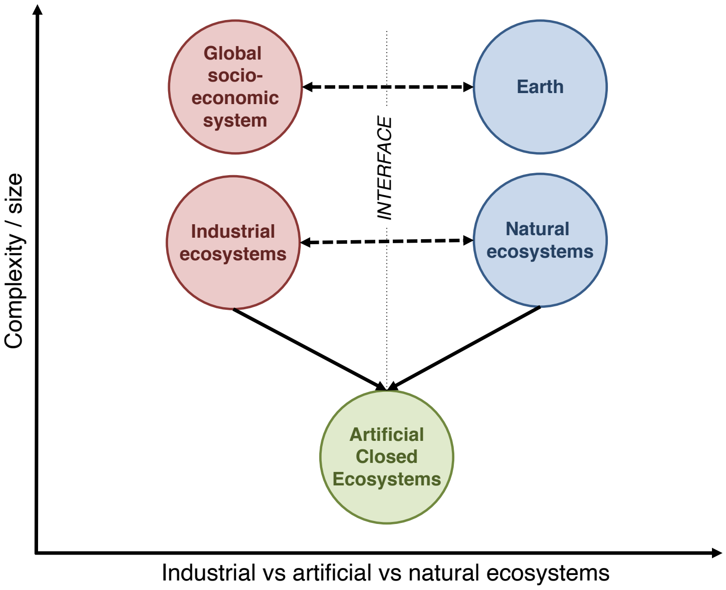

Figure 7: The ideal ACE positioning at the interface between natural and industrial ecosystems. Adapted from Suomalainen (2012) and Besson and Erkman (2016).

In this respect, Erkman (2004) argued there is a wide spectrum of industrial ecosystems interacting more or less directly with the biosphere, from agricultural ecosystems, almost 'natural' to the urban ecosystems, and up to the more artificial ecosystems, such as spacecraft. Given its hyper-artificialisation, a space ACE can be considered as an example of a natural environment taken to the extreme, an 'ultimate' industrial ecosystem.

In his visionnary essay on Earth as a spaceship[133], Boulding (1966)[134] discussed the 'closed economy

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[132] Cf §2.2.

[133] Cf §13.4.

[134] Excerpts from Boulding (1966): 'The closed earth of the future requires economic principles which are somewhat different from those of the open earth of the past. For the sake of picturesqueness, I am tempted to call the open economy the 'cowboy economy,' the cowboy being symbolic of the illimitable plains and also associated with reckless, exploitative, romantic, and violent behavior,

of the future' and made a distinction between the portions of the GNP which are derived respectively from exhaustible and renewable ('reproducible') resources. He notably proposed to put in place a material flow accounting to know which part of economic system output would be back into it as an input. He also called this concept the 'space economy', for which the context be the most extreme in terms of closedness. Applied to space ACE, this concept implies that the resource management fully corresponds to the one of type III ecosystem[135], that is, of a closed circular system. At the first glance, the conception of a global type III system seems impossible to attain under real-life conditions, unless potentially in the form of a CH doted with an ACE[136].

Basically, space-based ACE face the same constraints but more strongly as terrestrial systems do. While resources on Earth are limited by economic, environmental and energy costs, in space the mass of ALSS is the main limiting factor, given the exorbitant costs of launching this type of equipment. Furthermore, although terrestrial resources have their absolute physical limits, there is currently some flexibility in their choice: when one resource runs out, it is usually possible to source an equivalent within the same material resource category. In contrast, the amount of resources carried on board a shuttle is fixed and cannot be easily increased, while resupply during the mission will certainly not be possible to fill in the waste released that could not be recycled. Consequently, it is imperative that resources are recirculated in the system as efficiently as possible, so that as little waste as possible is emitted.

As Suomalainen points out in her thesis manuscript at UNIL (2012), what is striking about bioregenerative LSS is their level of 'isolation'. An isolation that, in some aspects, can be compared to isolated location such as islands or even to the Earth system as a whole: interactions with the external environment are limited and the resources within the system are the only ones easily accessible. According to Deschenes and Chertow (2004), islands face problems of limited resource availability and fragile security of supply, as well as strictly limited environmental support capacity. While mainland populations also face these issues, they need to be addressed more urgently in island systems where achieving sustainable development is crucial. In other words, while at the scale of a land-based continent, sustainability concerns are about the more or less distant future, the decisions taken in an island system immediately influence its sustainability. The situation is even more restrictive for a space ACE as an extreme example of an island system, since directly exploitable resources are mostly available in extremely limited quantities making them almost often close to its carrying capacity.

Nonetheless, contrarily to the space travel, an ACE based on a planet or satellite may be surrounded by abundant but hardly exploitable resources. Consequently, the situation might change as resources to supply the space ACE can be extracted from the extraterrestrial environment, through the exploitation of local resources, namely in situ resource utilisation (ISRU)[137]. ISRU makes it possible to envisage greater flexibility, for example by benefiting from an external supply of carbon through the valorisation

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which is characteristic of open societies. Tile closed economy of the future might similarly be called the 'spaceman' economy, in which the earth has become a single spaceship, without unlimited reservoirs of anything, either for extraction or for pollution, and in which, therefore, man must find his place in a cyclical ecological system which is capable of continuous reproduction of material form even though it cannot escape having inputs of energy. The difference between the two types of economy becomes most apparent in the attitude towards consumption. In the cowboy economy, consumption is regarded as a good thing and production likewise; and the success of the economy is measured by the amount of tile throughput from the "factors of production," a part of which, at any rate, is extracted from the reservoirs of raw materials and noneconomic objects, and another part of which is output into the reservoirs of pollution. If there are infinite reservoirs from which material can be obtained and into which effluvia can be deposited, then the throughput is at least a plausible measure of the success of the economy. The gross national product is a rough measure of this total throughput. It should be possible, however, to distinguish that part of the GNP which is derived from exhaustible and that which is derived from reproducible resources, as well as that part of consumption which represents effluvia and that which represents input into the productive system again. Nobody, as far as I know, has ever attempted to break down the GNP in this way, although it Would be an interesting and extremely important exercise, which is unfortunately beyond the scope of this paper.'

[135] Cf §3.8.1.

[136] Cf §13.4.

[137] Cf §15.6 and Annex A-§10.4.2

of CO_2 (production of synthetic biofuel, expansion of crops in the Martian greenhouses, synthesis of bio-based products, etc.)[138], although this requires a significant amount of equipment that will probably have to be sent to the landing site beforehand. Therefore, ISRU gives the possibility to progressively extend colonies first settled on Mars. In any case, resources that can be exploited through ISRU should be circularised as much as possible. Nevertheless, space conditions impose a slow rate of growth of the crew habitat and ACE compared to what man can build on Earth. Such restricted pace of development for humans drives the implementation of a sustainable growth in space CH, even when such development is mainly based on ISRU.

When operating under the radical conditions of the space context, ACE (ALSS) can be envisioned as one of the most extreme case of industrial ecosystem. Therefore, space ACE undeniably constitutes a relevant model and experimental framework for the analysis of industrial ecosystems operating under extreme constraints. As illustrated in Figure 8, space ACE (ALSS), LSS and ACE can also be considered as nested systems within industrial and natural ecosystems.

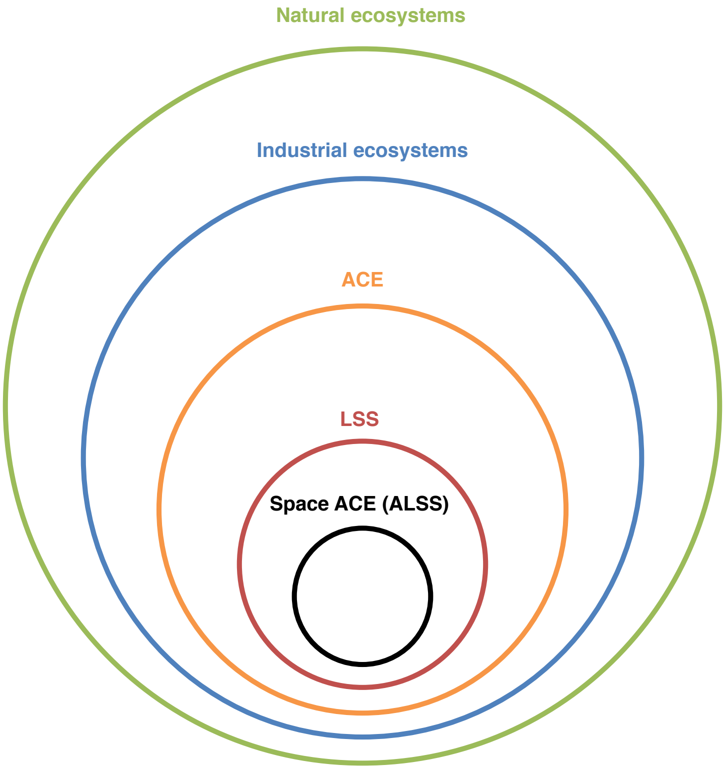

Figure 8: Space ACE (ALSS), LSS and ACE as nested systems within industrial and natural ecosystems.
Space ACE reduce their biosphere into the most basic biological processes to sustain its functions. Thus, they can simply be seen as waste convertor and raw material regenerator (oxygen, water, food). By mimicking and shortening biogeochemical cycles, ALSS can also be considered as miniaturised, simplified and minimal natural ecosystems, obviously strongly artificialised. In the context of this dissertation, ALSS are considered as a special case of LSS related to extraterrestrial domain, which is itself a specific category of ACE, so that ALSS correspond to space ACE. ACE being one of the many types of industrial ecosystems. As discussed earlier[139], industrial ecosystems are themselves particular components of natural ecosystems.

As a recycling system, Erkman (2004) also noted that a space ACE is a response to a question posed

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[138] Cf Annex A-§7.4.3.4.

[139] Cf §2.2.

by Robert Frosch (Frosch & Gallopoulos 1989): ‘What would be the equivalent industrial organisations decomposers?’[140]. In this case, the decomposers come from the biosphere, but they are selected and grown under conditions determined by man. The system can control exactly the entrants as well as waste by-products and outgoing products, including playing on the conditions of temperature and acidity. Moreover, thanks to genetic engineering, bacterial strains could be obtained with very specific properties, unknown in natural ecosystems, at least yet..

As space ACE are still not fully circular at the current stage of technological development, they cannot be considered as perfect industrial ecosystems. Despite the extreme conditions under which it operates, a space ACE remains rather a simplified – even if extreme – case of an industrial ecosystem, since it does not interact with the natural terrestrial environment (in particular when located on an alien planet). The situation is therefore obviously not as complex as the economic system or a natural ecosystem composed of several hundred or even thousands of species. Nevertheless, the integrated lifelike technologies of space ACE made them much closer to reality than many oversimplified experimental models, such as those available in research laboratories today[141].

In summary, space ACE can be considered as highly sophisticated, efficient and resource-saving quasi-circular systems whose technical operation has been optimised to the maximum extent to sustain life in extreme conditions, and which should allow ultimately for the full recycling of material flows in space habitats. Therefore, a ground simulator of such minimal case of a ‘hybrid’ ecosystems should be envisaged as an novel experimental platform for testing a whole series of high technologies needed not only to prepare for a ‘Mars Mission’, but also those likely to drastically improve the environmental performance of recycling systems.

In the light of the above, a space ACE or ALSS should clearly be seen as a models for industrial ecosystems under extreme constraints.

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[140] As a side note, it is worth to mention that Frosch was the former administrator of NASA between 1977 and 1981, which closes the history loop and bridges with space ALSS.

[141] Cf §6.1.

As a conclusion for Part I, Figure 9 contextualises the scope of research question 1 (RQ1) 'What is the relevance of ACE research to the conceptual foundations of IE?' along the research domains of IE and LSS.

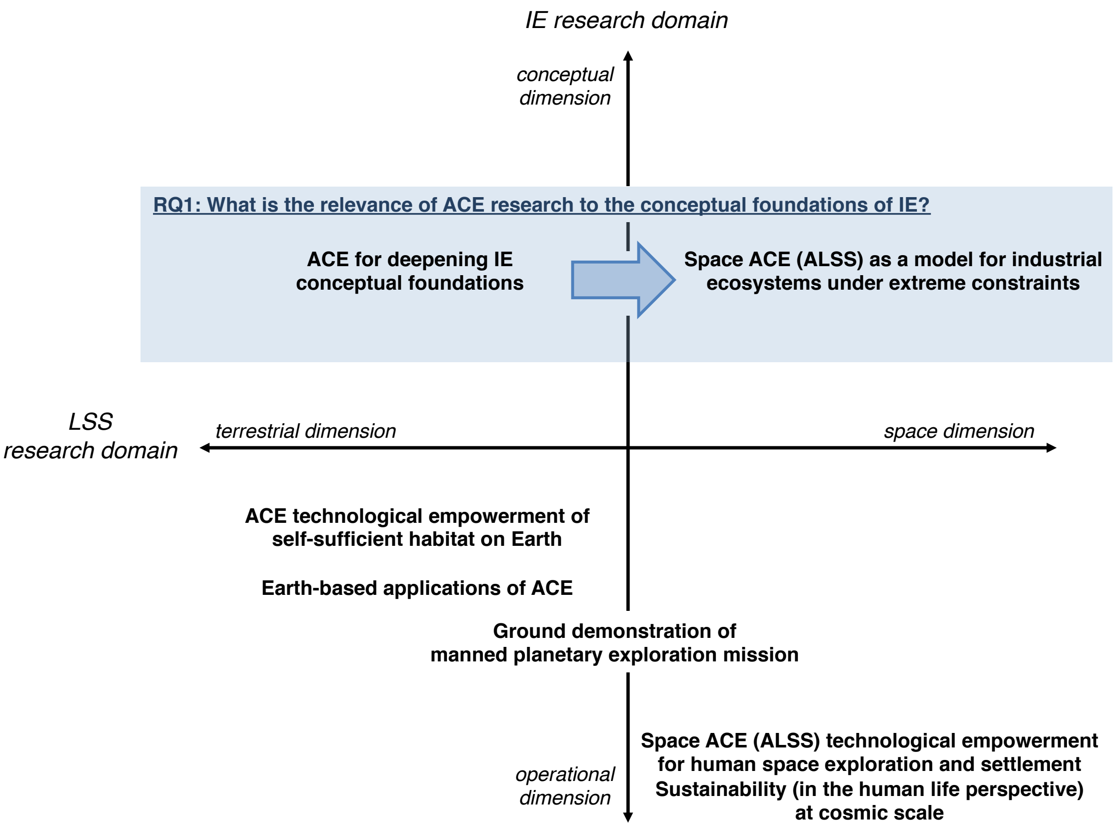

Figure 9: Scope of the research question RQ1 along the research domains of IE and LSS.
The first part of this PhD thesis studies the relevance of ACE research to the conceptual foundations of IE (RQ1). It reviewed the analogy between the natural and industrial ecosystems, proposed key concepts for ACE analysis in the perspective of IE and examined space ACE (ALSS) as models for industrial ecosystems under extreme constraints.

In conclusion, as the reception of ACE theory in the direction of IE has been rather preliminary so far, Part I attempted to clarify the potential, relevance and interest of ACE in order to consolidate the conceptual foundations of IE (RQ1). By leveraging the study of integral recycling loops in the context of an expanding society and a world of finite resources, ACE can be considered as relevant tools for the maturation of industrial ecosystems. All in all, this first part demonstrated that ACE development represents an excellent compromise and has an untapped potential for developing further the theoretical basis of IE.

PART II: CROSS-FERTILISING THE TERRESTRIAL AND SPACE DIMENSIONS OF LIFE SUPPORT SYSTEMS DEVELOPMENT (RQ2)

The second part of this work focuses on the possible ways to cross-fertilise the terrestrial and space dimensions of LSS development (RQ2).

Chapter 5 formulates a preliminary research agenda for the Oïkosmos science and technology programme (RO2.1). In particular, it illustrates how a full-scale crewed ACE ground demonstrator for preparing manned planetary exploration in the most realistic closed-loop conditions would leverage and intensify the implementation of a space and terrestrial research agenda on ACE. Chapter 5 shows that Oïkosmos, as a synergistic R&D programme on ACE, comprises a mapping of a broad range of research topics for the fields of IE, systems biology, ICT and closed and sustainable habitat.

Chapter 6 assesses the ways to develop and exploit a ground demonstrator of ACE as a technological platform for the study of circular systems (RO2.2). It conceptualises the opportunities for knowledge and technology transfer it offers, and maps the multiple modalities of use, operational activities and services that such technology platform provides to the actors of the Research-Innovation-Market value chain. As the cornerstone of the Oïkosmos programme, the ACE demonstrator could have a life of its own by offering spaces for promoting innovation, science and technology: conference and seminar rooms, exhibition halls, restaurants, etc. The gradual development of additional activities and of a network of skills through a forum, a competence centre and an incubator would make the simulator's environment – already technically favourable – conducive to exchanges of technological and commercial experience and practices, making it more than a series of ultramodern infrastructures adapted to the needs of its tenants, users and clients. Chapter 6 concludes that a dynamic could thus form around the ACE demonstrator to compete for access, space, equipment and expertise around its technological platform, in the same way that physicists compete to use the few particle accelerators available, or astronomers compete for access to large-scale telescopes.

Chapter 7 presents a position paper on the 'consolidation of the Swiss activities and rationale for ALSS and MELiSSA development'. More particularly, the paper explores, maps and assesses the Swiss activities, interests and strengths in LSS (RO2.3), in the framework of MELiSSA roadmap. As an outcome, Chapter 7 shows evidence that the current timing appears highly adequate for consolidating the Swiss activities and rationale for ALSS into an active and productive cluster; for positioning Switzerland as a key player in space and terrestrial ALSS; as well as for allowing an increased international visibility for Switzerland in the field of manned space exploration.

Chapter 8 demonstrates the terrestrial and space research synergy potential through the elaboration and consecutive implementation of a concrete R&D project (spin-in or spin-out) (RO2.4), with the concrete example of the BELiSSIMA project (spin-out). In particular, Chapter 8 shows how such ACE-based project could be used to observe the effects of various microcompounds (such as endocrine disruptors, biocides, etc.) and trace elements on several categories of species under test conditions that are more realistic than those of a laboratory.

Chapter 9 illustrates a possible co-development technology roadmap with an exemplifying prototyping projects series (RO2.5) – the SUMIT projects – which presents a potential both for spin-in and spin-out pathways. It discusses the usefulness of the SUMIT urinalysis devices using miniaturised sensors, not only for the non-invasive monitoring of crew health, but also for the overall functionality of ALSS (e.g. regulation of the urine loading to a downstream nitrification process, proper nutrition of food plants, prevention of scaling in water recovery processes, etc.).

Chapter 10 then presents the proceedings of the ESA Closed Habitat Forum 2016. This event is one of the components of the stakeholder engagement strategy for consolidating the current Swiss activities and rationale for LSS and MELiSSA development into an active and productive cluster (RO2.6.c), together with the position paper (RO2.6.a), and BELiSSIMA Phase A (RO2.6.b).

Chapter 11 aims to demonstrate the opportunities offered by the hosting of an ACE ground demonstrator based in Western Switzerland for its innovation ecosystem and for the Swiss space sector (RO2.7). It highlights the advantages of the region's participation in the development of an ACE demonstrator, which represents a way: to strengthen Swiss institutional participation in ESA activities – which seems all the more relevant since ESA sometimes has difficulties in financing space projects carried out in Switzerland; to bring together under a single umbrella a unique panel of strategic technologies for Switzerland, within a platform integrating interdisciplinarity upstream of its development, from the early R&D phases; to consolidate the existing dynamics between economic promotion, entrepreneurship and innovation; and to strengthen the region's position as a centre of excellence on the European eco-innovation map. It concludes that it would be desirable for Western Switzerland to develop an institutional strategy in favour of its participation in the Oïkosmos programme and to encourage the progressive setting up of an ACE demonstrator in the region.

Chapter 12 explores some of the possible ways to foster the institutional dynamics for ACE and LSS development in Switzerland and promote related education and communication activities (RO2.8). In particular, it proposes accompanying measures, recommendations and suggestions to the Direction of the University of Lausanne. It also presents the pedagogical concept around the teaching unit EPFL ENAC Building on Mars.

5 Oïkosmos programme - Terrestrial and space research synergies on ACE (RO2.1)[142]

In its second part, Oïkosmos Report (Annex A) identifies, maps and details the synergies of terrestrial and space research that could take place within an ACE demonstrator or CH simulating facility, as per RO2.1. This chapter first introduces the synergistic approach of the Oïkosmos programme (§5.1), it then describes the methodology use for the elaboration of the Oïkosmos research agenda (§5.2). The next sections summarise the research synergies related topics studied in Oïkosmos in the field of IE (§5.3), systems biology (§5.4), information and communication technologies (§5.5), and closed and sustainable habitat (§5.6). Eventually, final considerations on the Oïkosmos programme are provided in §5.7.

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[142] Related research outputs:

- §5.1 is adapted from Annex A-§4.2.3;
- §5.2 to §5.7 provide an overview of the Oïkosmos Report Part II (Annex A-§5 to §11);
- For an overview of the Oïkosmos Report structuration, see Figure 58.

5.1 The synergistic approach of the Oïkosmos programme

Research objective RO2.1 aims to map the possible synergies from the terrestrial and space research on ACE, synergies that could be established within the framework of a programme called 'Oïkosmos', fully detailed in Annex A-Part II. This section first wishes to define this notion of 'research synergy' and introduce the 'synergistic' approach which is at the heart of the present work.

Etymologically, the term 'synergy' comes from the Greek *sunergia*, meaning 'cooperation', which itself comes from *sun-* 'with, together' and *ergon* 'work'. This concept can therefore be translated literally as 'working together'. Interestingly, the French dictionnary *Le Grand Robert de la langue française* defines a 'synergy' from a physiological point of view as 'a coordinated action of several organs, a combination of several factors that contribute to an action, to a unique effect'[143], referring to a drug or muscle synergy. The *Oxford English Dictionnary completes* the definition with 'the production by two or more agents, substances, etc., of a combined effect greater than the sum of their separate effects'.

By analogy, the research synergies under study here involve bringing together the research scientists and engineers from space disciplines and from terrestrial (ie. 'non-space') ones, to collaborate in a coordinated manner towards a common goal. This collaboration can take many forms, such as the pooling of knowledge and/or material resources, to achieve a specific effect mutually beneficial for their respective research. In pharmacology, a 'drug synergy' means that the *simultaneous* administration of, for example, two antibiotics can produce additive effects that are stronger than the sum of the individual effects of each of the two substances administered separately (or sequentially). In the context of Oïkosmos, one of the objectives of establishing a successful research synergy could thus be to bring out new and original research results through the combination and coordinated coupling of terrestrial and space-based research. By analogy to a 'muscle synergy' – for the execution of a given movement through the coordinated contraction of several muscles – a research synergy encourages the pooling of the respective dynamics from stakeholders from the space and non-space fields, bringing them in return a reciprocal added value.

In the context of this work, the Oïkosmos programme is thus emerging as a project on the convergence between space and terrestrial research. It is interested in the potential, relevance and opportunities offered by the establishment of research synergies that could be established in the framework of the in-depth study of ACE and the operation of a ground-based simulator preparing human missions to Mars under the most realistic conditions possible. In particular, it is a question of identifying which fields, themes and research topics can be of interest to both terrestrial and space research.

If the terrestrial benefits of interdisciplinary research on space LSS have long been recognised (Mitchell et al. 1996), the particularity of Oïkosmos is the intimate association of its research program with its ad hoc facility dedicated to experiments in a CH in which a crew evolves during medium to long duration simulation campaigns. Chapter 14 will specifically discuss the contributions of the synergistic research on ACE – and of space and terrestrial ACE development in general – to terrestrial sustainability.

The portmanteau word 'Oïkosmos' was chosen as the name of the project in 2004, at the suggestion of Prof. Suren Erkman, and results from the contraction of 'oikos' (the house, the Earth), and 'kosmos' (the universe). Oïkosmos succinctly expresses the 'dual' nature of the research programme: both connected to space as well as oriented towards sustainable development on Earth[144].

This research program suggests that the implementation of synergies can thus initially spring from the terrestrial or the space dimensions, before becoming – by definition – bidirectional in its exchanges

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[143] Définition de 'synergie' selon Le Grand Robert de la langue française (2017): 'Action coordonnée de plusieurs organes, association de plusieurs facteurs qui concourent à une action, à un effet unique.'

[144] §5.6 details the onomastic of Oïkosmos.

between the two communities of researchers.

In this perspective, Chapter 5 summarised the preliminary research agenda listed in Annex A-Part II, research synergies presenting one and/or the other of the following relevance:

✧ *Relevance of the space mission to terrestrial research*

The specific needs related to man's presence in space and the responsibility for his health, well-being and reliable performance are driving forces for the development not only of space technologies, but also of solutions that improve the lives of ‘earthlings’. The Oïkosmos programme aims to enhance a transfer of knowledge from space to earth (‘spin-out’) and encourage numerous technological developments leading to the creation of terrestrial applications useful to European citizens, to take the example of some of the expected societal returns from ESA activities.

For instance, spaceflight induces changes in the body such as bone loss, reduced immune function, or altered work capacity. The development of countermeasures to these effects is essential to ensure that the health and performance of crew members and astronauts is maintained. However, such symptoms are caused on Earth by the natural aging processes of organisms, certain diseases or working conditions. Research on ‘space’ countermeasures is of interest to address terrestrial issues of human health management, and to help better understand and manage certain diseases.

As mentioned above, planetary exploration missions could also have interesting terrestrial spin-out in the field of ‘terrestrial sustainability’, complementary to those that we already benefit from on a daily basis – and whose importance continues to grow – through telecommunications, satellite navigation or meteorological services, etc. In concrete terms, research on closed systems also makes it possible to envisage the development of interesting applications on Earth[145], such as highly efficient systems for recycling organic waste in the current context of increasing scarcity of material resources[146], or for early warning detection of pollution with the growing dissipation of pollutants in natural ecosystems.

✧ *Relevance of terrestrial research to the space mission*

Reversely, the Oïkosmos program aims to ensure the transfer of knowledge from Earth to space (‘spin-in’) and enable the testing, consolidation and validation of the state of the art of terrestrial research, and of the most emerging associated technologies, in the ACE demonstrator.

For example, the design and conception of the CH demonstrator could make use of the best available terrestrial ecotechnologies to maximise the air and microbial quality of the indoor environment[147], and of the best ‘omics’ technologies to monitor the health of the molecular systems present in the ACE (e.g. genome, proteome, metabolome, nutrigenome…[148].

Let us now look at the activities that have allowed, in the framework of this PhD study, to formulate a research agenda for the Oïkosmos program.

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[145] Cf §14.2.

[146] Biostyr® is, for example, a technology is based on the results of research carried out in MELiSSA compartment III. Developed in collaboration with Veolia, this solution enables a clear improvement in the nitrification process. In Europe, several million cubic metres of wastewater are recycled every day using this technology in wastewater treatment plants based in cities such as Rome, Paris, Lyon and Zaragoza.

See ‘BIOSTYR technology derived from MELiSSA patent’, published on ESA website on 22.05.2015: https://www.esa.int/ESA_Multimedia/Images/2015/05/BIOSTYR_technology_derived_from_MELiSSA_patent (last retrieved on 01.05.2020).

[147] Cf Annex A-§6.2.2 and Annex A-§10.5.

[148] Cf Annex A-§6.3 and Annex A-§8.2.

5.2 Methodological introduction

Figure 10 provides an overview of the Annex A-Part II.

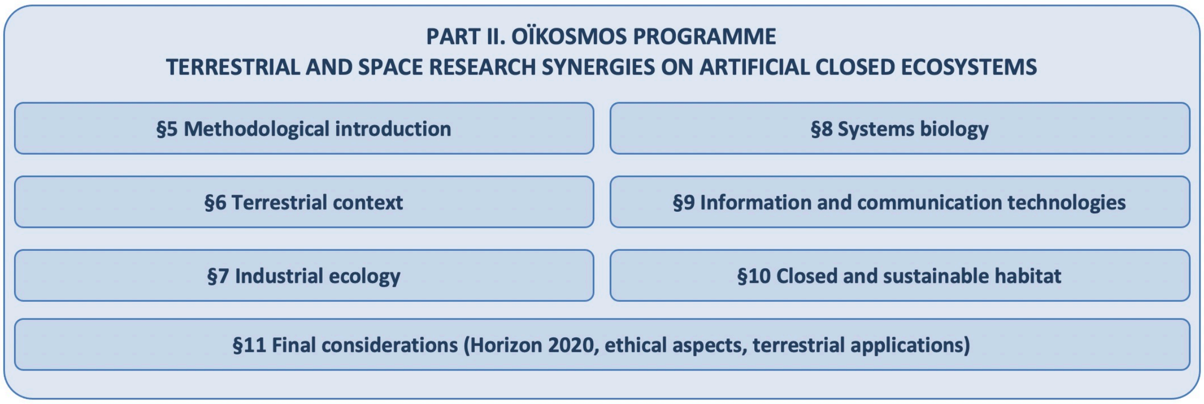

Figure 10: Structuration for the Part II of the Oïkosmos Report (Annex A-Part II).

The methodology that allowed the formulation of the Oïkosmos research agenda (Annex A-§5) is presented in this section. Subsequently Annex A-§6 is devoted to the terrestrial context and explores some of the major trends in Europe that can be pertinently associated with the issue of ACE and CH (Annex A-§6.1). It then focuses on three disciplinary fields that have a strong potential for establishing terrestrial and spatial synergies in the framework of the Oïkosmos programme, respectively the field of IE, systems biology and of information and communication technologies (Annex A-§6.2 to 6.4).

The following chapters (Annex A-§7 to §11) constitute the core of the research agenda related to Oïkosmos. They detail, articulate and investigate the research synergies related to the fields introduced in §6, namely :

✧ for the disciplinary field of industrial ecology (Annex A-§7) :

- *the deepening of the concepts, strategies, methodologies and tools of industrial ecology (Annex A-§7.2);*
- *the fine-tuning and the optimisation of the ecosystems conditions (Annex A-§7.3);*
- *the development of highly efficient recycling systems (Annex A-§7.4).*

✧ for the disciplinary field of systems biology (Annex A-§8):

- *biomonitoring and maintenance of the health of organisms: from genomics to metabolomics (Annex A-§8.2) :*
- *nutrition: from food production to nutrigenomics and microbiomics approaches (Annex A-§8.3).*

✧ for the disciplinary field of information and communication technologies (Annex A-§9):

- *computational sciences (Annex A-§9.2);*
- *embedded technologies (Annex A-§9.3);*
- *telehealth (Annex A-§9.4).*

✧ to the notion of closed and sustainable habitat (Annex A-§10), at the convergence of the three above-listed disciplinary fields, in connection with related concepts:

- *eco-habitat (Annex A-§10.2);*
- *self-sufficient habitat (Annex A-§10.3);*
- *autonomous habitat (Annex A-§10.4);*
- *healthy habitat (Annex A-§10.5);*
- *smart habitat (Annex A-§10.6).*

✧ final considerations (Annex A-§11) cover:

- *the reinforcement of the integration of Oïkosmos programme in Horizon 2020 (Annex A-§11.1);*
- *ethical aspects of living in closed habitat (Annex A-§11.2);*
- *the Earth-based applications of ACE (Annex A-§11.3).*

The methodology that allowed the formulation of Oïkosmos research agenda[149] is presented in this section. In order to formulate a preliminary research agenda for the Oïkosmos science and technology programme dedicated to the establishment of space and terrestrial research synergies on ACE (RO2.1), the following activities were carried out[150] (see Figure 11):

- Identification of the preliminary scope of the Oïkosmos programme[151];
- Mapping of research domains for the establishment of research synergies in Western Switzerland[152];
- Consolidation of the scope of the report[153];
- Formulation of a research agenda for the Oïkosmos programme[154].

Subsequently, the formulated research agenda is first contextualised with current terrestrial challenges[155] and then extensively detailed within four key research domains illustrating potential terrestrial and space research synergies on ACE based on ESA/MELiSSA LSS development roadmap, respectively as follows:

- Industrial ecology[156];
- Systems biology[157];
- Information and communication technologies[158];
- Closed and sustainable habitat[159].

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[149] Cf Annex A-§5.

[150] Cf Annex A-Part II.

[151] Cf §5.2.1.

[152] Cf §5.2.2.

[153] Cf §5.2.3.

[154] Cf §5.2.4.

[155] Cf Annex A-§6.

[156] Cf §5.3 - Annex A-§7.

[157] Cf §5.4 - Annex A-§8.

[158] Cf §5.5 - Annex A-§9.

[159] Cf §5.6 - Annex A-§10.

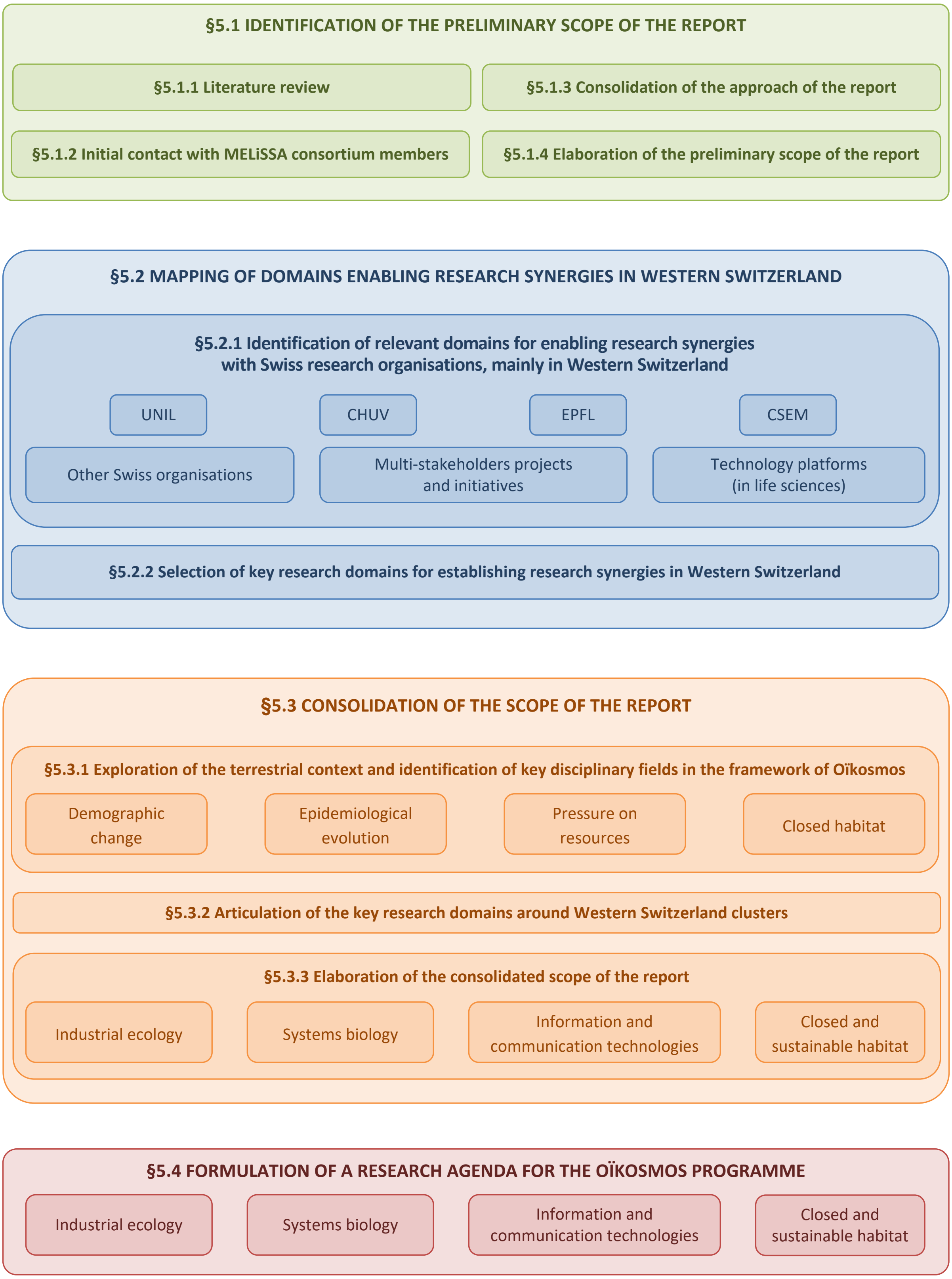

Figure 11: Methodology of the Part II of the Oïkosmos Report (Annex A-Part II).

5.2.1 Identification of the preliminary scope of the Oïkosmos programme

The following activities were performed to identify the preliminary scope of the Oïkosmos programme (Figure 12):

- Literature review based on the initial scope of the report;
- Initial contact with MELiSSA consortium members;
- Consolidation of the report approach[160];
- Elaboration of the preliminary scope of the report[161].

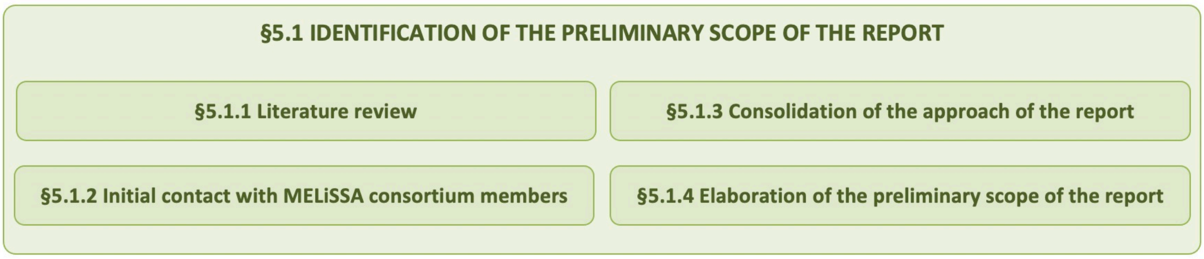

Figure 12: Identification of the preliminary scope of the Oïkosmos programme (Annex A-§5.1).

5.2.1.1 *Approaches used for the Oïkosmos programme*[162]

✧ *A systemic approach*[163]

In the context of Oïkosmos, the use of a 'systemic' approach, sometimes also called a 'global' or 'holistic' approach, makes it possible:

- to integrate the complexity of a ACE as a whole: its structure, its functioning, its mechanisms, its environment, its level of organisation, etc.[164];
- to understand the dynamics and feedback loops of a ACE: the factors regulating its homoeostasis, the interactions between its subsystems[165];
- to study and quantify the effects of a disturbance on all the systems of molecules (such as the genome, proteome, metabolome, etc.) present in an organism at a given moment[166].

This is not a strict opposition between reductionist and holistic approaches, but simply the application of a systems approach to a simplified system, namely the ACE.

✧ *A biomimetic approach*

Biomimicry[167] essentially consists in taking inspiration from the operating principles of the 'Biosphere'

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[160] Cf §5.2.1.1.

[161] Cf §5.2.1.2.

[162] This section summarises the approaches used for the Oïkosmos programme detailed in Annex A-§5.1.3.

[163] This approach is also discussed in Annex A-§6.2.3 on IE, Annex A-§7.3.4 on the regulation of homoeostasis, and Annex A-§8 on systems biology.

[164] Cf §3.1.

[165] Cf §3.2.

[166] Cf §5.5.

[167] Cf Annex A-§7.3.1.4.

and transforming this inspiration into innovation. The biomimetic approach seeks to study the Biosphere by developing bioinspired solutions, with the following objectives:

- to exploit its mechanisms in order to apply them in different technological fields (*bionics*);
- to facilitate its scientific study by reproducing it in the laboratory (*biophysics*);
- to draw inspiration from the organisation of ecosystems (and the functioning of the living beings that make it up) in order to better integrate human organisation and technologies (*biomimicry*).

✧ *A 'life-cycle' approach*[168]

As a key part of the conceptual framework of IE, the 'life cycle' approach aims to reduce as much as possible the impacts of activities, products and services of the industrial ecosystem, over their entire life cycle, i.e. 'cradle-to-grave' or even 'cradle-to-cradle'.

In the field of systems biology[169], it is also a question of being able to apprehend the life cycle of molecules circulating within ACE, space habitats and in general, from their synthesis by or outside organisms from organic or inorganic molecules, to their biological or physico-chemical degradation in or outside organisms, via their effect on the expression of the genes of a given organism.

✧ *An interdisciplinary and integrative approach*[170]

The Oïkosmos programme calls upon multiple fields and disciplines not directly concerned with space until now[171]. This presupposes an interdisciplinary an integrated approach[172], which favours the exploration, identification and selection of research themes and topics that allow building bridges with subjects initially 'indirectly' related to the study of ACE and space habitats.

Such a meta-approach can be considered as integrative. In the scientific context, meta- means 'beyond' and is used to refer to concepts that 'encompass' others. Within the Oïkosmos programme, the categorisation and mapping of research themes should also facilitate their interconnections and build bridges between them, ultimately leading to the establishment of interdisciplinary research, whether or not related to the space domain. This is particularly the case for research at the convergence of new information and communication technologies and the field of IE[173] or that of biomedical sciences[174].

✧ *A collective and collaborative strategy*

On the basis of this integrative approach, the Oïkosmos programme implies that stakeholders from all disciplines can, as a matter of principle, interact strongly through a collective and cooperative strategy. The aim is therefore to foster the participation and collaboration of communities of researchers from the various disciplines formulated in the research agenda[175]. However, it emerges from the report that many of them do not (yet) perceive today that they could be directly concerned by such a project. One of the challenges is therefore to encourage them to participate and to demonstrate to them the potential added value of integrating their skills, both from a space and terrestrial point of view, via research synergies. It

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[168] This approach is discussed in Annex A-§7.2.5 on the improvement of the assessment of impacts using the life cycle assessment methodology

[169] Cf §5.5 and Annex A-§8.

[170] The interest of an ACE demonstrator for interdisciplinary research is discussed in Annex A-§16.

[171] Cf §5.1.

[172] Cf Annex A-§16.

[173] Cf Annex A-§9.3.

[174] Cf Annex A-§9.4.

[175] Cf Annex A-§7 to §10.

should be noted that these stakeholders are not limited to academic research institutions alone, but include all the players in the Research-Innovation-Market value chain[176].

Oïkosmos Part III returns to the aspects of cooperation between public and private institutions[177]. The Position Paper presented in §7 also highlight the ongoing and possible future collaborations from the emerging Swiss cluster on ALSS.

✧ *An operational strategy*

The Oïkosmos programme could (and should, given the scale of the necessary investments) have important spin-offs for terrestrial applications[178], in terms of knowledge and technology transfer, particularly in the fields of industrial ecology, systems biology, information and communication technologies and microtechnologies. The deployment of an operational strategy[179] should make it possible to industrialise some of the technologies and innovative solutions developed in the framework of research on ACE, as is already the case today for water treatment systems.

Thanks to its systemic, interdisciplinary and integrative, collective and cooperative approach, as welle as its operational strategy[180], the deployment of Oïkosmos would notably 1) highlight the sometimes intimate – and even hidden – links between terrestrial research and numerous 'space' subjects and disciplines, and 2) demonstrate the intrinsic relevance and potential of an ACE demonstrator to maximise research synergies.

Taken together, these approaches and strategies leverage the cross-fertilisation between space disciplines and non-space research, and the establishment of a synergistic research agenda on ACE. They also served, to a lesser extent, to identify knowledge and technology transfer opportunities described in the case for an ACE demonstrator in Western Switzerland[181].

5.2.1.2 Preliminary scope of Oïkosmos programme[182]

The early exchanges with the MELiSSA project management and the initial review of the feasibility studies of FIPES done at the start of the Oïkosmos Report led to the conclusion that the three main domains of the Oïkosmos research agenda that could (should) be conducted within an ACE demonstrator cover LSS (functioning of cycles, life in isolated and confined environments), medical and psychological aspects, as well as biosafety. The initial scope was completed with the domain of industrial ecology, which was clearly part of the interest of the Direction of UNIL to perform such study in the perspective of sustainability.

As a result of the Oïkosmos activities[183] implemented with the synergistic approach describes above[184], the preliminary consolidated scope of Oïkosmos programme could be developed, which included the

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[176] Cf Annex A-§20.2, Annex B1 and Annex C2.

[177] Cf §11.

[178] Cf §14.2.

[179] As summarised in §6, Annex A-Part III details these aspects of knowledge and technology transfer.

Afterwards, §9 illustrates a possible co-development technology roadmap with an exemplifying prototyping project (RO2.5) - the SUMIT projects - which presents a potential both for spin-in and spin-out pathways for a health and ALSS biomonitoring device.

[180] Cf Annex A-§5.1.3.

[181] Cf Cf Annex-Part III.

[182] This section summarises the preliminary scope of the Oïkosmos programme elaborated in Annex A-§5.1.4.

[183] Cf Annex A-§5.1.1 to §5.1.3.

[184] Cf §5.1.

following relevant research domains, namely the following scientific and technological areas:

- Life support systems: cycle functioning, bioregeneration, bioaccumulation, (eco)toxicology, survival in autonomous mode, systems engineering, applied mathematics, instrument and equipment maintenance;
- Life sciences: medicine: effects of isolation and containment, antibiotic resistance; human physiology; telemedicine, circadian rhythms, nutrition; biology: microbiology, plant physiology, plant biology, cellular and molecular biology;
- Control of biological and chemical risks: detection and identification of contaminants, biosafety in confined environments, treatment and countermeasures;
- Social sciences: psychology: group behaviour, cooperative processes, cooperation in isolated and confined environments; data management: data mining, information processing;education and communication sciences;
- Industrial ecology: life cycle analysis, metabolism of material and energy flows, integrated management and optimal use of environmental resources, highly efficient recycling systems, eco-technologies for water, air and organic waste valorisation, energy efficiency.

5.2.2 Mapping of research domains for establishing research synergies in Western Switzerland

The preliminary scope was used as a basis for the mapping of research domains that could establish research synergies in Western Switzerland (see Figure 13). To do so, the following activities were conducted:

- Identification of relevant research domains for establishing research synergies with Swiss research organisations, mainly in Western Switzerland;
- Selection of key research domains for establishing research synergies in Western Switzerland.

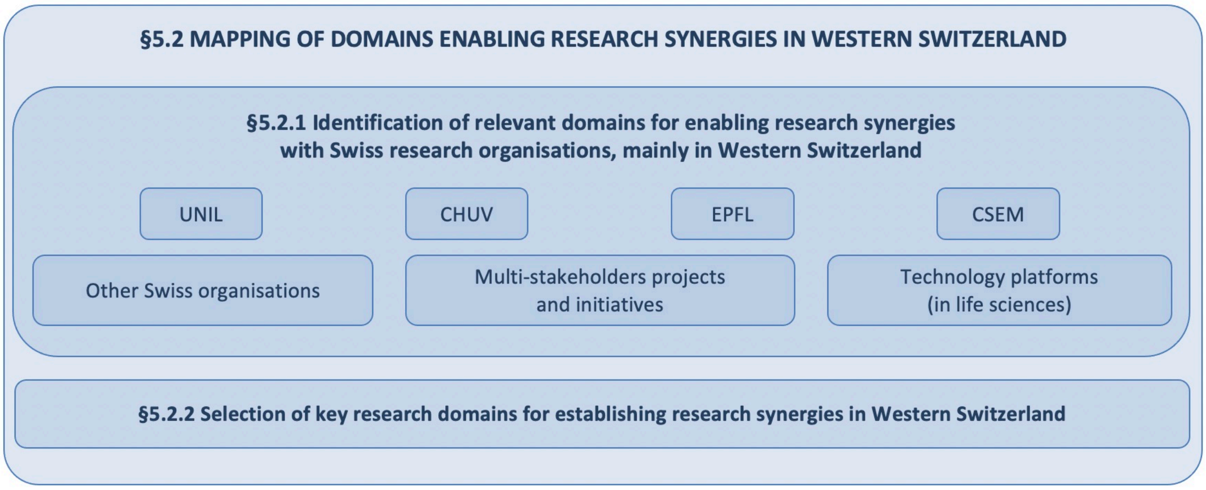

Figure 13: Mapping of research domains for establishing research synergies in Western Switzerland (Annex A-§5.2).

The contacted researchers were mainly active in non-space fields related to the Oïkosmos programme preliminary scope. The interviews were conducted according to an agenda generally composed of the following points:

- Presentation of the Oïkosmos research programme: its objectives, approach, activities, examples of potential research synergies;
- Collection and analysis of additional unpublished information from the stakeholders met;
- Assessment of the potential of research domains, themes and topics specific to the work carried out by the research groups met, promoting research synergies, within the framework of the Oïkosmos programme;
- Evaluation of the interest of establishing research synergies with the activities of the research groups contacted;
- Study of possible opportunities for collaboration, as well as their modalities, within the framework of the development and operation of a ground-based simulating facility;
- Identification of other researchers and research institutions with potential and possible interest in establishing research synergies and/or collaborating in the Oïkosmos programme;
- When relevant: visiting the laboratories of the research groups met.

A total of eighty interviews were conducted out of a total of over 300 screened research groups.

As a result of these interviews, it was possible to identify, select, compile and map the most relevant domains for the establishment of first tracks of terrestrial and space research synergies with research groups from Swiss academic institutions (Figure 13), namely :

- the University of Lausanne (UNIL): 60 research groups identified[185];
- the Centre Hospitalier Universitaire Vaudois (CHUV): 14 research groups/services identified[186];
- the Ecole Polytechnique Fédérale de Lausanne (EPFL): 105 research groups identified (listed in)[187];
- the Swiss Centre for Electronics and Microtechnology (CSEM): research domains identified in each CSEM division[188];
- Over 25 research groups identified in other Swiss research institutions such as Université de Genève (UNIGE), Université de Neuchâtel (UniNE), Université de Fribourg (UniFR), Université de Berne (UniBE), Hôpitaux universitaires de Genève (HUG), Haute Ecole Spécialisée de Suisse occidentale (HES-SO), Eidgenössische Technische Hochschule Zürich (ETHZ), Hochschule Luzern (HSLU), Eawag, EMPA and PSI[189];
- multi-partner projects and initiatives conducted by Swiss research institutions: the Human Brain Project, the national initiatives SystemsX.ch and Nano-Tera, the Smart Living Lab (now part of EPFL), the Swiss Integrative Center for Human Health (UniFR), the EssentialTech project (EPFL), the Anthropos programme (UNIL) and the Ethos platform (UNIL)[190];
- Over 25 technology platforms in life sciences based in Western Switzerland covering notably the fields of imagery, genomics and bioinformatics, proteomics and chemical analysis[191].

On the basis of these interviews, a brief catalogue of arguments in favour of, but also against, such

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[185] Cf Annex A-§5.2.1.1.
[186] Cf Annex A-§5.2.1.2.
[187] Cf Annex A-§5.2.1.3.
[188] Cf Annex A-§5.2.1.4.
[189] Cf Annex A-§5.2.1.5.
[190] Cf Annex A-§5.2.1.6.
[191] Cf Annex A-§5.2.1.7.

opportunities for collaboration (synergistic or not) was drawn up[192].

In addition, the contacts made it possible to select the key research domains of the consolidated scope[193], and then to enrich and the research agenda[194] through an iterative process.

For more details on the contact parties, see the summary table 'Stakeholders in Western Switzerland' (see Excel file attached the Annex A), which:

- summarises the research groups and units associated with the departments and institutes of the above faculties;
- details for each of them the key words associated with their research activities (relevant fields, themes and research topics);
- prioritises the research groups and units that seem most relevant for establishing synergies (priority 1 to 3);
- proposes a mode of participation in the Oïkosmos programme, for example:
    - participation in the steering committee;
    - participation in the project committee;
    - participation in the consultation committee;
    - participation in a thematic working group.

On the basis of the above-mentioned review of the research domains, the following key research domains in Western Switzerland were selected[195]:

- Life sciences:
    - biology:
        - systems biology ('omics' sciences): genomics, proteomics and metabolomics;
        - bioinformatics, computational systems biology;
        - bioengineering, biomolecular simulations and modelling, biomedical imaging, bioimaging, neurosciences;
        - plant biology, plant metabolism, plant nutrition.
    - medicine:
        - genomic medicine, personalised medicine, biomedicine, molecular and translational medicine;
        - human physiology: human metabolism, sleep, circadian rhythms, movement sciences and sports medicine, exercise physiology, energy homoeostasis;
        - food: functional nutrition, nutrigenomics, food biotechnologies;
        - exposure sciences: occupational health, (bio)chemical analysis by mass spectrometry, pharmacokinetic analyses and measurements, therapeutic monitoring of drug administration, clinical toxicology.
- Environmental sciences, technologies and engineering:
    - industrial ecology: analysis of material and energy flows, life cycle assessments; eco-technologies, cleantech, energy efficiency;
    - pollution of the natural and built environment: transformation of pollutants, remediation techniques, environmental toxicology, molecular ecotoxicology; environmental microbiology, bioremediation, natural treatments;

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[192] Cf Annex A-Part IV

[193] Cf Annex A-§5.2.2.

[194] Cf Annex A-§8 to §11.

[195] Cf Annex A-§5.2.2.

    - sustainable habitat, autonomous buildings.
- Engineering:
    - green microtechnologies: photovoltaic, water treatment;
    - precision engineering: microfabrication processes, hardware miniaturisation;
    - microelectronics and smart systems: integrated electromechanical microsystems, low consumption embedded electronics.
- Information and communication technologies:
    - new information and communication technologies: mobile and ubiquitous computing, mobile technologies, wireless communication systems, embedded information systems, portable biosensing;
    - smart monitoring: smart sensors, wireless sensor networks, remote sensing, geographical information systems;
    - smart habitat: intelligent buildings, building automation, home automation.
    - computer and communication engineering: data mining, image processing, information visualisation, multimedia information systems, biomedical signal processing; interaction sciences and technologies: human-machine interfaces, augmented reality, computer vision, highly miniaturised camera systems.
    - computational and computer sciences: modelling of complex systems, dynamic modelling, artificial intelligence, machine learning.
- Humanities:
    - psychology: psychosociology, group behaviour, cooperation processes, sociology (communication, interdisciplinarity);
    - decision support systems, organisational behaviour;
    - technology management, innovation management.

5.2.3 Consolidation of the scope of the Oïkosmos Report

The following activities were performed to consolidate the scope of the Oïkosmos Report (Figure 14):

- exploration of the terrestrial context and identification of key disciplinary fields in the framework of Oïkosmos[196];
- articulation of the key research domains around Western Switzerland clusters[197];
- on this basis, elaboration of the consolidated scope of the report[198].

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[196] Cf Annex A-§5.3.1.

[197] Cf Annex A-§5.3.2.

[198] Cf Annex A-§5.3.3.

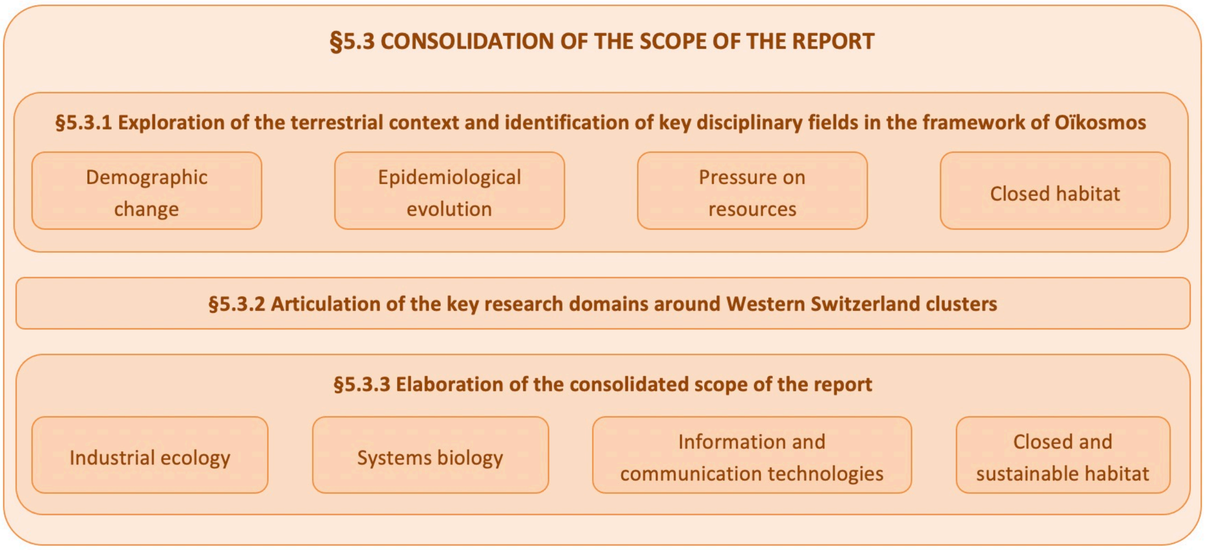

Figure 14: Consolidation of the scope of the Oïkosmos programme (Annex A-§5.3).

First of all, the exploration of the terrestrial context was carried out[199] which enabled the identification of major trends which reinforced the relevance of the Oïkosmos programme, namely:

- demographic change: an ageing European population[200];
- epidemiological trends: a European population affected by chronic diseases, exposed to environmental pollution, and exhibiting risky behaviours[201];
- environmental performance improvement: an essential step forward in a context of ever-increasing pressure on resources[202];
- the growth in the constraints to which tomorrow's terrestrial habitats will be exposed, i.e. in the perspective of closed habitat[203].

It emerged from this activity that the key research domains for the Oïkosmos programme can be grouped into three disciplinary fields, whose development has been significantly growing in recent years:

- industrial ecology[204];
- systems biology and omics sciences[205];
- information and communication technologies[206].

On the other hand, from the perspective of CH, a fourth field seemed to be relevant for Oïkosmos, namely the notion of closed and sustainable habitat[207]. The themes related to this notion call upon the research fields of industrial ecology (eco-housing, autonomous habitat, self-sufficient habitat), systems biology (healthy habitat) and information and communication technologies (smart habitat).

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[199] Cf Annex A-§5.3.1.
[200] Cf Annex A-§6.1.1.
[201] Cf Annex A-§6.1.2.
[202] Cf Annex A-§6.1.3.
[203] Cf Annex A-§6.1.4.
[204] Cf Annex A-§6.2.
[205] Cf Annex A-§6.3.
[206] Cf Annex A-§6.4.
[207] Cf Annex A-§10.

On the basis of the research domains identified in the previous activities, the technology clusters of Western Switzerland and the associated key technology promotion agency were then selected[208].

The key technology clusters in Western Switzerland are:

- energy and environment;
- biotechnology and pharmaceuticals;
- nutrition and consumer products;
- medical technologies and high technologies related to health;
- micro and nanotechnologies and precision engineering;
- information and communication technologies.

The associated key technology promotion agencies are:

- CleantechAlps: environmental technologies, cleantech;
- Energie-Cluster: energy, eco-technologies;
- BioAlps: life sciences, biotechnology, medtech;
- Medical Cluster: medical technologies;
- Swiss Food Research: food industry;
- Micronarc: micronanotechnologies, precision engineering ;
- AlpICT: information and communication technology ;
- Information Systems & IT Cluster (ISIS): information systems, multimedia, computer applications and security.

It should be noted at this stage that most of the scientific and technological clusters in the region can be considered relevant, in one way or another, for the study of ACE.

Next, the key research domains and key clusters in Western Switzerland were compiled and structured around the four above-mentioned disciplinary fields. The resulting consolidated scope of the Oïkosmos Report is composed as follows[209]:

- **Industrial ecology**. Research domains and associated chapters of the research agenda:
    - industrial ecology[210], scientific ecology, ecosystem homoeostasis[211];
    - exposure sciences ('exposome'[212]), ecotoxicology and molecular environmental sciences[213], indoor environmental health and occupational health[214];
    - environmental technologies[215], carbon dioxide recovery[216], biorefinery[217].
- **Systems biology**. Research domains and associated chapters of the research agenda:
    - systems biology, omics sciences[218];

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[208] Cf Annex A-5.3.2.

[209] Cf Annex A-5.3.3.

[210] Cf Annex A-§6.2 and §7.2.

[211] Cf Annex A-§7.3.4.3.

[212] Cf Annex A-§7.3.3.1.a.

[213] Cf Annex A-§7.3.3.1.b.

[214] Cf Annex A-§7.3.3.2.c.

[215] Cf Annex A-§7.4.1 (valorisation of organic waste), Annex A-§7.4.2 (water purification) and Annex A-§10.5 (air regeneration).

[216] Cf Annex A-§7.4.4.

[217] Cf Annex A-§7.4.5.

[218] Cf Annex A-§6.3 and §8.

    - genomics, transcriptomics and proteomics[219], as well as metabolomics[220];
    - human physiology (endocrine regulation); circadian rhythms[221];
    - plant biology: plant culture; plant metabolism[222];
    - nutrigenomics[223], functional nutrition[224];
    - microbiomics[225].
- **Information and communication technologies**. Research domains and associated chapters of the research agenda:
    - computational sciences: computer sciences and computational biology[226];
    - embedded technologies[227]: smart monitoring and MEMS-type microsystems[228];
    - new information and communication technologies (NICT): mobile and ubiquitous computing[229];
    - interaction sciences and technologies: human-machine interfaces[230];
    - telehealth, telemedicine[231].
- **Closed and sustainable habitat**. Research domains and associated chapters of the research agenda:
    - sustainable habitat[232]: eco-habitat[233]; self-sufficient habitat[234]; autonomous habitat[235]; healthy habitat[236]; smart habitat[237].

5.2.4 Formulation of a research agenda for the Oïkosmos programme

The final activity in Part II of the Oïkosmos Report [238] was to formulate a preliminary research agenda for the Oïkosmos programme.

First of all, the four disciplinary fields from the consolidated scope of the report served as a canvas for the articulation of the terrestrial and space research synergies in the perspective of ACEs (Figure 15).

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[219] Cf Annex A-§8.2.1 to §8.2.4.
[220] Cf Annex A-§8.2.5.
[221] Cf Annex A-§8.2.6.
[222] Cf Annex A-§8.3.1.2.
[223] Cf Annex A-§8.3.2.2.
[224] Cf Annex A-8.3.2.3.
[225] Cf Annex A-§8.3.3.
[226] Cf Annex A-§9.1.
[227] Cf Annex A-§6.4.2 to §6.4.3 and Annex A-§9.3.
[228] Cf Annex A-§9.3.1 to §9.3.2.
[229] Cf Annex A-§6.4.1 and Annex A-§9.3.1
[230] Cf Annex A-§9.3.5.
[231] Cf Annex A-§9.4.
[232] Cf Annex A-§6.1.4 and Annex A-§10.1.
[233] Cf Annex A-§10.2.
[234] Cf Annex A-§10.3.
[235] Cf Annex A-§10.4.
[236] Cf Annex A-§10.5.
[237] Cf Annex A-§10.6.
[238] Cf Annex A-Part II.

Figure 15: Formulation of a research agenda for the Oïkosmos programme (Annex A-§5.4).

Following this, an in-depth study enabled the identification and compilation of the themes and research topics associated with these synergies, as well as for some of them, possible experiments, tests, procedures and potential protocols.

This research agenda, described in the sections below §5.3 to §5.7 seeks to demonstrate in a concrete way how the synergies of research proposed in the present study are relevant for the efficient experimentation on ACE. In particular, it seeks to foster interactions between scientists, engineers and technicians from the terrestrial and space communities, within a dedicated ground ACE demonstrator[239].

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[239] Cf Annex A-Part III.

5.3 Investigations at the frontiers of IE research[240]

The synergies of space and terrestrial research from the investigations at the frontiers of IE are detailed in Annex A-§7 of the Oïkosmos Report .

The relevance of IE to the Oïkosmos programme is first introduced[241]. ACE demonstrator seems capable of acting as a real 'Swiss knife' for both the generation and the analysis of the flows that circulates within ecosystems[242]. These flows enter, leave and pass through the various compartments composing the ACE, thus constantly varying their respective contents. They are, of course, flows of materials and energy, but also flows of information and knowledge. More particularly:

- Industrial ecology treats an ACE as an industrial ecosystem and focuses on the flows of materials (and energy) through it;
- Systems biology consider an ACE as a biological ecosystem and focuses on the flows of molecules that circulate within it;
- Information and communication technologies see an ACE as an informational ecosystem and focus on the flows of information and knowledge generated and propagated within it.

More concretely, an ACE demonstrator is a toolbox for carrying out various research activities – implemented not successively, but in a correlating way –, with the following objectives:

- measurement and detection: to analyse, understand and interpret ecosystem material flows[243];
- modelling and simulation: to predict, anticipate and evaluate ecosystem risks[244];
- piloting, operation and optimisation: to produce the various components of the ecosystem, manage and valorise its flows, as well as improve the ecosystem as a whole, in routine situations – but in extreme conditions –, during the daily activities of the crew[245];
- environmental and health biomonitoring: to monitor and control the exposome[246] in order to control risks, diagnose a disorder and identify its cause(s); assessing meticulously the effects of the exposome on the health of the organisms[247];
- maintenance of ACE homoeostasis within predefined limits and application of countermeasures: to response, actively influence, regulate and perpetuate the ecosystem; to prevent, treat, and cure the negative effects and impacts of the exposome on the health of organisms, including in unforeseen, exceptional or emergency situations[248].

The implementation of these R&D activities should optimise the operational processes of the ACE, in order to ensure its sustainability initially for the whole simulation campaign on Earth, with the ultimate

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[240] Related research outputs:
- For an introduction of the conceptual foundations of IE, see §2 (RO1.1).
- For a review of the key concepts for ACE analysis in the perspective of IE, see §3 (RO1.2)
- For exploring space ACE as a model for industrial ecosystems under extreme constraints, see §4.3 (RO1.3).
- For a general introduction of the field of IE, within the framework of the Oïkosmos programme, see Annex A-§6.2 of the Oïkosmos Report (in French).
- For an overview of the operational aspects of IE, see Annex C2a-§7 in BELiSSIMA Phase A TN118.1.4.

[241] Cf Annex A-§7.1.1.

[242] Cf Annex A-§7.1.2.

[243] Cf Annex A-§7.3.3.2.d on the analysis of the distribution of micropollutants and chemical contaminants.

[244] Cf Annex A-§9.2.1 on mathematical modelling of complex systems.

[245] Cf Annex A-§7.3.2 on optimising the performance of micro-organism cultures.

[246] Cf Annex A-§7.3.3.

[247] Cf Annex A-§8.2.

[248] Cf Annex A-§7.3.4.3 on adaptive capacity to changes in ecosystem conditions.

objective of carrying it out during an entire ‘Mars mission’.

The following sections of Oïkosmos Report (in French) are an integral of part of the research output from this PhD study.

The way the field of IE benefit from the modelling and simulation of ACE will be discussed, and notably at the level of the use of the traditional analytical methodologies of IE (e.g. MFA or LCA) but also as a mean to extend them with new insights and tools from biological sciences.

For the field of IE research, Oïkosmos Report first focuses on the use of an ACE simulating facility for the deepening of the concepts, strategies, methodologies and tools of IE[249]:

- a framework for the consolidation of the concept of IE[250];
- a model for the ecorestructuring of the industrial ecosystem[251];
- a vector for the development of dynamic material flow analysis[252];
- a laboratory for testing, modelling and developing ‘industrial’ food networks[253];
- a driving force for improving the assessment of impacts (life cycle assessment methodology)[254];
- a support for the development of the notion of systemic sustainability[255].

Oïkosmos Report then discusses the ACE demonstrator as relevant infrastructure for the fine-tuning and optimisation of ecosystems conditions[256]:

- an instrument for improving our knowledge on ecosystems[257]:
  - monitoring of accelerated biogeochemical cycles in near real-time[258];
  - operating on a ‘meso’ complexity scale[259];
  - observing interactions at the ‘organism-habitat-environment’ interfaces[260];
  - exploring and testing the principles of biomimicry in extreme conditions[261].
- a driver for the optimisation of microorganisms culture in (photo)bioreactors[262];
- an experimental platform for biomonitoring the exposome[263]:
  - control of biological and chemical risks[264]: exposome and ecotoxicology;
  - hypermonitoring of the exposome[265]: environmental risk assessment, detection via early warning systems, monitoring of biological, chemical and physical exposures, and analysis of the distribution of microcompounds and chemical contaminants.
- a regulator of the homoeostasis of organism and their ecosystem[266]:

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[249] Cf Annex A-§7.2.
[250] Cf Annex A-§7.2.1.
[251] Cf Annex A-§7.2.2.
[252] Cf Annex A-§7.2.3.
[253] Cf Annex A-7.2.4.
[254] Cf Annex A-§7.2.5.
[255] Cf Annex A-§7.2.6.
[256] Cf Annex A-§7.3.
[257] Cf Annex A-§7.3.1.
[258] Cf Annex A-§7.3.1.1.
[259] Cf Annex A-§7.3.1.2.
[260] Cf Annex A-§7.3.1.3.
[261] Cf Annex A-§7.3.1.4.
[262] Cf Annex A-§7.3.2.
[263] Cf Annex A-§7.3.3.
[264] Cf Annex A-§7.3.3.1
[265] Cf Annex A-§7.3.3.2.
[266] Cf Annex A-§7.3.4.

    - homoeostasis of organisms[267];
    - homoeostasis of ecosystems[268]: ecological stoichiometry, dynamic energy budget theory, artificial ecological successions, artificial ecopoiesis;
    - enhancing adaptive capacity to changing ecosystem conditions[269]: resilience, blind prediction, ‘massively parallel’ architecture, self-repair;
    - implementation of of preventive measures[270];
    - application of corrective measures (countermeasures)[271].

Finally, Oïkosmos Report describes how the Oïkosmos programme could be leveraging the development of highly efficient recycling systems (integral recycling)[272]:

- a driving force for ecotechnologies development[273];
- a facilty for the decentralised treatment of organic waste[274];
- an experimental testbed for the chemical and biochemical valorisation of carbon dioxide[275]:
    - carbon dioxide: a resource to be recovered and no longer a waste to be captured and stored[276];
    - carbon dioxide: an exploitable source of carbon in the context of ACE[277];
    - strictly closed artificial ecosystem[278];
    - semi-closed artificial ecosystem, with external CO_2 supply[279]: biological pathway, chemical pathway.
- the biorefinering of the by-products of ACE[280].

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[267] Cf Annex A-§7.3.4.1.
[268] Cf Annex A-§7.3.4.2.
[269] Cf Annex A-§7.3.4.3.
[270] Cf Annex A-§7.3.4.4.
[271] Cf Annex A-§7.3.4.5.
[272] Cf Annex A-§7.4.
[273] Cf Annex A-§7.4.1.
[274] Cf Annex A-§7.4.2.
[275] Cf Annex A-§7.4.3.
[276] Cf Annex A-§7.4.3.1.
[277] Cf Annex A-§7.4.3.2.
[278] Cf Annex A-§7.4.3.3.
[279] Cf Annex A-§7.4.3.4.
[280] Cf Annex A-§7.4.4.

5.4 Investigations at the frontiers of systems biology research[281]

When artificialising ecosystems, the constant monitoring of the organisms evolving in them is essential to maxime the system performance. The context of Oïkosmos makes it appropriate to simultaneously monitor the various factors determining the state of health in a CH. The biomonitoring of the health of the ACE requires the fine monitoring of its exposome[282]. This includes, in addition to the physico-chemical conditions, the microbes, micropollutants, drugs or other bioactive molecules such as hormones and proteins present at a given moment in the system, and to which the organisms of the ecosystem are subjected in their immediate environment. The effects of environmental conditions on the internal environment of the organisms[283] in the ACE can be investigated using a systemic approach[284], in particular the modifications induced by the exposome on the genomic and epigenomic[285] content, as well as the associated metabolic responses.

According to Calvert (2013), systems biology is currently one of the most prominent large-scale endeavours in the life sciences, which might be considered as a good example of 'big science'. Oïkosmos Report seeks to demonstrate the contribution of the disciplines associated with the field of systems biology to the ongoing monitoring of the overall health of ACE organisms[286]. Systems biology[287] is a branch of modern science that aims to significantly improve the understanding of the dynamic interactions between organic molecules and cellular components that take place within a biological system. The methodologies and tools of this field provide a relevant framework for studying the impact of ecosystem conditions on the functioning of living organisms in the ACE. In particular, the omics sciences make it possible to biomonitor the health of humans living in CH, microorganisms in (photo)bioreactors, and crops grown in plant chambers. Also, ACE imply to reckon that one of our most limited life support eco-artifacts depends on the microbiome that composes ourselves and on microbial communities essential for continuous materials regeneration and waste valorisation.

Within the framework of the Oïkosmos programme, the appropriate research synergies related to systems biology concern the analysis and monitoring of the flows of molecules composing organisms and/or circulating within ecosystems, and in particular within a CH demonstrator. This study considers as a priority the integration of the following omics approaches, methodologies and technologies, as described in recent publications: genomics, transcriptomics (Quintens et al. 2020; B. Wang et al. 2021), proteomics (Sachdeva et al. 2018; Ilgrande et al. 2018; Bayon-Vicente 2020) and metabolomics (Scalbert et al. 2009; Baker 2011; Patti et al. 2012; Miller et al. 2019), as well as nutrigenomics (Wahli & Constantin 2011; Menni et al. 2012; Hesketh 2012) and microbiomics (Oriach et al. 2016; Farré-Maduell & Casals-Pascual 2019; Ezzeldin et al. 2019; Van Houdt & Leys 2020). These allow the detection, localisation and/or monitoring of elements of the ACE such as: genes and regulatory sequences of the epigenome involved in maintaining the good health of the cells of the ACE organisms; molecules (hormones or drug residues, micropollutants and other contaminants) circulating in the ACE to which crew members and other organisms in the ecosystem will be exposed; micro-organisms in the bioreactors and those present in the liquid streams, air and surfaces of the CH.

ACE species, and especially bacteries and microalgaes, will be more and more engineered in the future,

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[281] Related research output:

- For a general overview of the development of the field of systems biology, within the framework of the Oïkosmos programme, see Annex A-§6.3 of the Oïkosmos Report (in French).

[282] Cf Annex A-§7.3.

[283] The human internal environment includes, for example, the cell cytoplasm of tissues and physiological fluids such as interstitial fluid, blood, lymph and cerebrospinal fluid.

[284] Cf §5.2.1.1.

[285] Epigenomics deals with the regulation of gene expression related to non-coding DNA (see Annex A-§8.3.2.1).

[286] Cf Annex A-§8.

[287] Cf Annex A-§6.3.

thanks to modelling, screening and selection capacity from system biology, in order to efficiently and reliably regenerate air, produce edible biomass and drinkable water from crew waste flows. In particular, omics sciences have become essential to study and quantify the effects of a disturbance on all the systems of molecules (such as the genome, proteome, metabolome, etc.) present in an organism at a given moment.

Finally, even though living on Mars provides access to partial gravity that avoids many physiological disorders (e.g. bone loss), there are still the risks of radiation and extreme weather conditions, dust, etc. High quality nutrition is therefore a key factor.

The following sections of Oïkosmos Report (in French) are an integral of part of the research output from this PhD study.

For the field of systems biology research, Oïkosmos Report first describes the biomonitoring and health maintenance of ACE organisms: from genomics to metabolomics[288]:

- integrating omics approaches into crew genetic selection[289];
- analysis of regulatory pathways and genome dynamics of ACE[290];
- study of horizontal gene transfer phenomena in ACE[291];
- the interdependence between the exposome and the biological processes of the ACE[292];
- metabolomics: analysing the effects of the exposome on the metabolic pathways of the ACE[293];
- systems biology research in an ACE simulator (1/2): from genomics to metabolomics[294];
- exercise physiology: a non-omics approach to maintaining human health[295];
- synthetic biology: towards the creation of tailor-made metabolic functions for ACEs[296].

Later, Oïkosmos Report focuses on nutrition, from food production to nutrigenomics and microbiomics approaches[297]:

- Food production, processing and preparation systems: from crop to plate[298]:
    - plant characterisation and selection[299];
    - plant cultivation[300];
    - quality control of agri-food processes and products[301];
    - final preparation of food[302].
- Nutrigenomics: omics for nutrition optimisation[303]:
    - epigenomic changes induced by the exposome[304];
    - nutrigenomics: the study of the influence of nutrients on our genes[305];

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[288] Cf Annex A-§8.2.
[289] Cf Annex A-§8.2.1.
[290] Cf Annex A-§8.2.2.
[291] Cf Annex A-§8.2.3.
[292] Cf Annex A-§8.2.4.
[293] Cf Annex A-§8.2.5.
[294] Cf Annex A-§8.2.6.
[295] Cf Annex A-§8.2.7.
[296] Cf Annex A-§8.2.8.
[297] Cf Annex A-§8.3.
[298] Cf Annex A-§8.3.1.
[299] Cf Annex A-§8.3.1.1.
[300] Cf Annex A-§8.3.1.2.
[301] Cf Annex A-§8.3.1.3.
[302] Cf Annex A-§8.3.1.4.
[303] Cf Annex A-§8.3.2.
[304] Cf Annex A-§8.3.2.1.
[305] Cf Annex A-§8.3.2.2.

    - functional and personalised nutrition: for a prolonged healthy life[306];
    - nutrigenomics: a missing link between sequencing and personalised medicine?[307];
    - systems biology research in an ACE simulator (2/2): from nutrigenomics to personalised medicine[308].
- Microbiomics: analysing the influence of commensal microflora on the health of ACE organisms[309]:
    - the microbiome and its metagenome[310];
    - the challenges of microbial ecology in ACE[311];
    - microbiomics in ACE[312];
    - artificial intestines[313].

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[306] Cf Annex A-§8.3.2.3.

[307] Cf Annex A-§8.3.2.4.

[308] Cf Annex A-§8.3.2.5.

[309] Cf Annex A-§8.3.3.

[310] Cf Annex A-§8.3.3.1.

[311] Cf Annex A-§8.3.3.2.

[312] Cf Annex A-§8.3.3.3.

[313] Cf Annex A-§8.3.3.4.

5.5 Investigations at the frontiers of information and communication technologies research[314]

As stated by Hendrickx & Mergeay (2007), the engineering of ACE, in particular for 'systems used during space travel itself, requires extensive databases of detailed growth parameters, reconversion rates, food value characteristics and metabolic responses of all candidate life-support organisms to feed mathematical models to improve the system and maintain control.' From the perspective of IE, the ACE simulator can be considered as a toolbox for the analysis and regulation of material and energy flows circulating within ecosystems[315]. In addition, information and communication technologies (ICT) give such demonstrator an additional asset within the framework of the Oïkosmos programme, allowing the ACE to be considered as informational ecosystems (De Rosnay 1995). By focusing on the monitoring of information and knowledge flows, ICTs represent a relevant framework for the establishment of research synergies relating in particular to: computational sciences (Kitano 2002; Bassingthwaighte 2008; Poughon et al. 2009; Boscheri et al. 2012), embedded technologies (Young & Sutton 2017), and telehealth (La Torre et al. 2012; Martin et al. 2012; Tafforin 2013; Kanas 2014; PwC 2016). In combination, they can achieve a truly smart monitoring of the ACE, which encompasses accurate and almost real-time monitoring for fast fine-tuning and countermeasures implementation if any oscillation is detected at the molecular level, at the body level, as well as at the ecosystem level.

In consequence, the development and operation of ACE demonstrator will have the capacity to generate quantities of experimental data from bench-scale research to quasi closed-loop human habitation. A programme such as Oïkosmos helps exploiting to the best this information, making it easily accessible for interdisciplinary studies, with maximised synergy for terrestrial research.

The following sections of Oïkosmos Report (in French) are an integral of part of the research output from this PhD study.

For the field of ICT research, Oïkosmos Report first focuses on computational sciences[316]:

- Mathematical modelling of ACE processes[317];
- Characterisation and harmonisation of ACE omics data[318];
- Digital modelling of human biological data[319].

Next, Oïkosmos Report discusses embedded technologies[320]:

- Smart monitoring of environmental and health data[321];
- Data mining: towards exploitation of data relevant to ACE homoeostasis[322];
- Interaction sciences: towards user-friendly and optimised human-machine interfaces[323];

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[314] Related research outputs:

- For an analysis of the potential of ACE development for the technological empowerment of self-sufficient habitat on Earth, see §13;
- For a general overview of the development of the field of information and communication technologies, within the framework of the Oïkosmos programme, see Annex A-§6.4 of the Oïkosmos Report (in French).

[315] Cf §5.3.

[316] Cf Annex A-§9.2.

[317] Cf Annex A-§9.2.1.

[318] Cf Annex A-§9.2.2.

[319] Cf Annex A-§9.2.3.

[320] Cf Annex A-§9.3.

[321] Cf Annex A-§9.3.1.

[322] Cf Annex A-§9.3.2.

[323] Cf Annex A-§9.3.3.

- Cybersecurity: towards secure data collection and storage in the digital cloud[324].

Eventually, Oïkosmos Report explores the field of telehealth[325]:

- Towards prolonging life at home in good health through telehealth[326];
- From telemedicine to telehealth: towards a broadening of synergistic human health research in ACE[327];
- Telepsychiatry[328]:
    - Assessing the psychological state of individuals in closed habitats[329];
    - Psychosociology in closed habitat[330];
    - Monitoring relationships with support staff[331];
    - Psychophysiology of emotion and performance in closed habitat[332];
    - Preventive actions[333].

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[324] Cf Annex A-§9.3.4.

[325] Cf Annex A-§9.4.

[326] Cf Annex A-§9.4.1.

[327] Cf Annex A-§9.4.2.

[328] Cf Annex A-§9.4.3.

[329] Cf Annex A-§9.4.3.1.

[330] Cf Annex A-§9.4.3.2.

[331] Cf Annex A-§9.4.3.3.

[332] Cf Annex A-§9.4.3.4.

[333] Cf Annex A-§9.4.3.5.

5.6 Investigations at the frontiers of closed and sustainable habitat research[334]

At this point, it seems appropriate to remind of the onomastic of the research programme that is the subject of this study: 'Oïkosmos'. Etymologically, the Greek root oikos of this word refers to the notion of 'habitat' and 'house', while kosmos refers to 'world' and 'universe'. Oïkos is also the root of the terms 'ecology' (with -logy, from economics), the science that studies the environments in which living beings live and reproduce, as well as the relationships of these beings with the environment[335], popularised by Haeckel as early as 1866; and 'ecosystem', the basic ecological unit, formed by the environment and the animal and plant organisms that live there (ibid.), proposed by Tansley as early as 1935[336].

Oikos is thus closely related to the concepts of environment, habitat and house. These provide complementary perspectives on users and organisms living in a CH, namely micro-organisms, plants and, of course, humans. In order to clarify the scope of these terms in the context of this work, the following complementary elements are provided:

✧ *Environmental conditions*: the 'environment' is the place in which organisms find themselves. It includes what materially surrounds them (such as material objects or other living things), as well as the set of external conditions in which organisms live and develop. The conditions of a natural environment are characterised by abiotic (physico-chemical and climatic) and biotic (biological) factors in continuous interaction. The external environment is contrasted with the intracellular media and physiological fluids of the internal environment of organisms and can be summarised as everything that is outside a living organism and that is likely to have an effect on it. In this sense, it corresponds to the notion of exposome in the case of ACEs and enclosed habitats.

✧ *The functionalities of a habitat*, including in an ecological context, represent the ways in which organisms of the ACE are organised and populated in their environment[337]. For humans, they are the technically effective devices and facilities to meet their needs: in terms of safety of habitat users (e.g. shelter from the weather); in terms of security of supply (by allowing them to store their reserves and resources of water, food, etc.); by providing a social framework between the inhabitants; and providing means of communication to the outside world.

✧ *The comfort and conviviality of a house*: by 'house' we mean the dwelling in which users stay over time, i.e. a real living space. The house is generally considered to be a place where it is 'good to live', and is seen as a space that is conducive to conviviality and easy to access and use.

On the basis of the above elements, and in addition to its scientific objectives specific to space exploration missions, the Oïkosmos programme aims - by virtue of its synergistic vocation and its connection to ESA - to develop technical solutions that meet the future needs of Europeans. Some of these solutions could concern the habitats of tomorrow, capable of providing adequate environmental conditions for the health of users, both functional and user-friendly, optimising the material and energy resources available locally.

In the context of ACE, the challenge also lies in designing closed habitats that are as 'sustainable' as

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[334] Related research outputs:

- For a complementary discussion on the users-building symbiosis within a CH in the context of ESTEE SA, see §13;
- For a general overview of the development of the field of closed and sustainable habitat, within the framework of the Oïkosmos programme, see Annex A-§6.4 of the Oïkosmos Report (in French).

[335] Definition translated from the definition of 'Oïkos' in the French dictionary *Le Grand Robert de la langue française*

[336] Cf §2.1.

[337] §13.3.1 details the notion of human habitat.

possible, in the broadest sense[338].

The following sections of Oïkosmos Report (in French) are an integral of part of the research output from this PhD study.

For the field of closed and sustainable habitat research, Oïkosmos Report first addresses some of the relevant research synergies[339] that combine and integrate the concepts of:

- eco-habitat[340]: based on 'ecological' architecture and using eco-materials;
- self-sufficient habitat[341]: capable of recovering the organic waste of its users and able to produce all or part of their food and objects
- autonomous habitat[342]: promoting alternative energy sources such as nuclear power, using local resources for the production of fuels, equipped with energy-efficient and environmentally effective instrumentation, with optimised artificial and natural lighting systems, or capable of recovering new sources of energy such as body energy;
- healthy habitat[343]: allowing fine regulation of the health of the indoor environment and control of the (microbial) quality of the air and surfaces of the home; and optimising habitability, ergonomics, comfort and user-friendliness for its inhabitants;
- smart habitat[344]: with efficient telecommunication capabilities; and using advanced materials based on micronanotechnologies and new information and communication technologies.

The CH is considered here as a whole, with the living spaces available to the crew, and all equipment and infrastructure (ACE included). Its potential users include scientists carrying out studies in isolated locations (Antarctic station such as Concordia) or preparing a manned mission to Mars in an ACE simulator, as well as those of an astronaut crew on Mars (planetary base).

The industrial engineers concerned by the construction of a sealed habitat are primarily those involved in regulating the environmental conditions and increase its safety and operational excellence. CH are at the confluence of the research synergies presented in the three previous chapters. Thus, optimising the performance of a CH evolving under extreme conditions calls for numerous methodologies and technological solutions from the fields of IE, systems biology and (new) information and communication technologies. Table 8 summarises the connections between the above-listed concepts related to the notion of sustainable CH and these three disciplinary fields.

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[338] Cf §13.4.

[339] Cf Annex A-§10.

[340] Cf Annex A-§10.2.

[341] Cf Annex A-§10.3.

[342] Cf Annex A-§10.4.

[343] Cf Annex A-§10.5.

[344] Cf Annex A-§10.6.

		FIELD OF RESEARCH		
		Industrial ecology	Systems biology	Information and communication technologies
CLOSED AND SUSTAINABLE HABITAT	Eco-habitat	X		
	Self-sufficient habitat	X	X	
	Healthy habitat	X	X	X
	Autonomous habitat	X		X
	Smart habitat			X

Table 8: Connections between the research fields of the Oïkosmos Report [345] *and the concepts related to the notion of sustainable and closed habitat.*

Ultimately a completely and truly sustainable habitat, either on Earth or in space, should be simultaneously a self-sufficient, autonomous, healthy and smart habitat.

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[345] Cf Table 1 of Annex A-Part II.

5.7 Final considerations

As illustrated in this chapter and most particularly in Annex A-Part II, a full-scale crewed ACE demonstrator for preparing manned planetary exploration in the most realistic conditions in terms of loop closure would leverage and intensify the implementation of a space and terrestrial research agenda on ACE. As a synergistic R&D programme on ACE, Oïkosmos comprises a mapping of a broad range of research topics for the fields of IE, omics sciences, ICT and closed and sustainable habitat, and consists in one of the main research output of this PhD work (RO2.1).

The final considerations of the Part II of Oïkosmos Report are composed of the three following sections:

- Strengthening the integration into the Horizon 2020 programme[346];
- Ethical aspects of living in a closed habitat[347];
- Terrestrial applications in relation to the study of ACEs[348].

In conclusion, a programme such as Oïkosmos, conducted within an ACE simulator that facilitates research synergies, could thus eventually make it possible to respond to many terrestrial problems, such as those illustrated the report.

Figure 16 summarises the main themes covered in the second part of the report, which form the core of the Oïkosmos scientific and technological research programme. Together and in complementarity, they will participate in the monitoring and regulation of organisms and the environment within an ACE simulator, the so-called exposome[349]. The research synergies on ACE will accelerate the ground preparation of manned interplanetary missions, and ultimately ensure their feasibility and hopefully their actual success.

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[346] Cf Annex A-§11.1.

[347] Cf Annex A-§11.2.

[348] Cf Annex A-§11.3.

[349] Cf Annex A-§7.3.3.

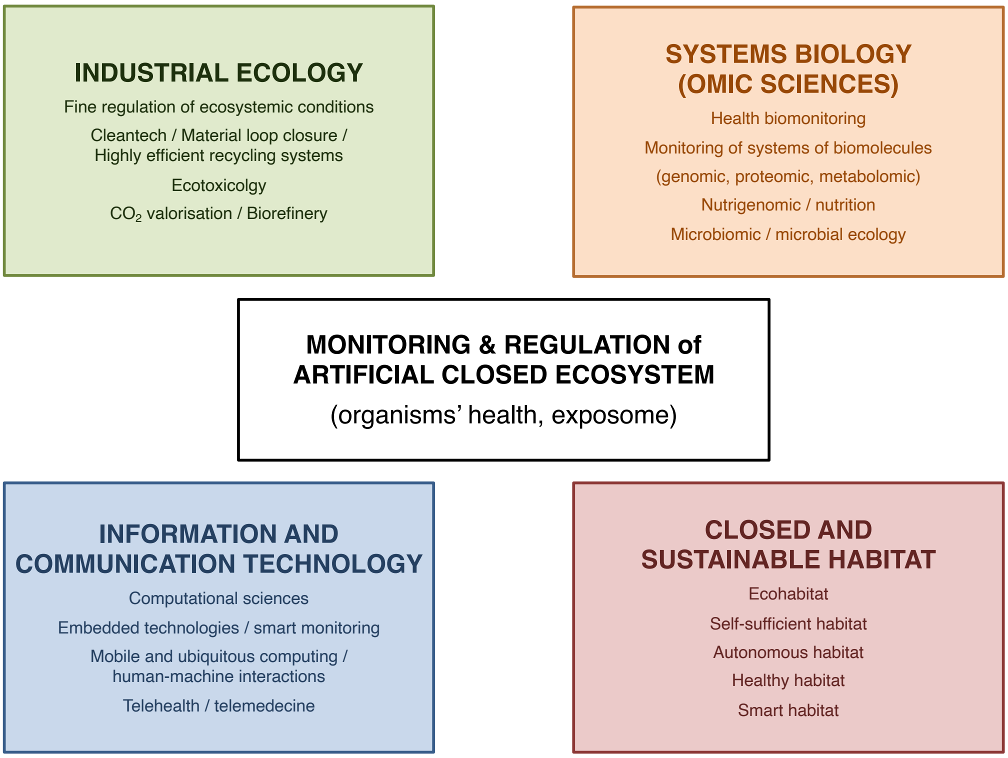

Figure 16: Summary of terrestrial and space research synergies on ACE addressed in Oïkosmos Report [350].

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[350] Cf Figure 21 of Annex A-Part II.

6 ACE ground demonstrator: a technological platform for the study of circular systems (RO2.2)[351]

For the purpose of assessing how to develop and exploit a ground demonstrator of ACE as a leading scientific and technological platform for the study of circular systems (RO2.2), Part III of Oïkosmos Report conceptualises the opportunities for knowledge and technology transfer it offers (Annex A-§12 to §20).

This section first discusses the ACE ground demonstrator as an essential testbed to address both space and terrestrial issues (§6.1). It then introduces the mapping of the multiple modalities of use, operational activities and services that such technology platform provides to the actors of the Research-Innovation-Market value chain (§6.2).

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[351] Related research outputs:

- §6.1 is adapted from Annex A-§4.2.2.2;
- §5 provides an overview of the Oïkosmos Report Part III (Annex A-§12 to §19);
- For an overview of the Oïkosmos Report structuration, see Annex A and Figure 19 (Annex A-Part III only).

6.1 The ACE demonstrator: an essential testbed to address both space and terrestrial issues

This section seeks to demonstrate the interest of deploying, within an ACE simulation facility, a research program to meet a dual objective, both from a space and a terrestrial perspective. First, because this technological demonstrator can be considered as a space analogue capable of faithfully reproducing some of the constraints specific to space habitats. Secondly, because a CH simulator seems to be a laboratory that is highly relevant for its terrestrial component in itself, independently of its space interest.

The space component specific to the testbed for the in-depth study of ACE is discussed in §6.1.1. Then, §6.1.2 envisaged the intrinsic terrestrial utility of this scientific laboratory. Finally, §6.1.3 considers the ACE demonstrator as an experimental platform for exploring the concept of systemic sustainability.

6.1.1 An analogue capable of faithfully reproducing some of the constraints specific to space habitats

As a reminder, the general constraints of traditional space habitats (ISS, lunar missions) are linked to extreme requirements in terms of reliability, logistics, size and performance[352]. Moreover, the design and development of space habitats for manned missions to Mars not only imply the reinforcement of these requirements, but also the addition of closed system constraints specific to long-duration missions and telecommunication delays due to long distances. Considering this formidable complexity, the conduction of ground simulation campaigns, within an ad hoc facility, becomes essential to maximise the feasibility and success of human interplanetary exploration.

Historically, demonstrators for ground preparation of manned space missions have been addressed in several studies such as HUMEX (Study on the Survivability and Adaptation of Humans to Long-Duration Interplanetary and Planetary Environments) (Horneck et al. 2002; Horneck et al. 2006) which concluded that facing the extreme conditions of in such mission requires a life support system; and REGLISSE (Review of European ground Laboratories and Infrastructures for Sciences and Support Exploration) (Comet et al. 2000), that highlighted the fact that no terrestrial demonstrator integrating an ACE – including humans – was available yet. Examples of ground simulation projects include DLR's ':envihab' (Koch & Gerzer 2011), that was planned to deal with extreme conditions of space habitats, or ESA and Roscomos' Mars500 project (Ngo-Ahn 2009) pursued to simulate confinement conditions within a CH. However, in spite of the intrinsic relevance of their scientific protocols, neither of both facilities integrated an advanced life-support system such as an ACE.

In this respect, well-known space testbeds aiming precisely at integrating bioinspired recycling system capable of producing food from organic waste should be mentioned, in particular the Closed Ecology Experiment Facilities (CEEF) in Japan (Nitta 2002; Tako et al. 2010; Sakai 2018), and the Lunar Permanent Astrobase Life-support Artificial Closed Ecosystem (Lunar Palace), China National Space Administration research closed facility for developing a moon base in closed conditions (Dong et al. 2015; Dong et al. 2016; Fu et al. 2016; Dong, Fu, Xie, M. Wang & Liu 2017a). The Chinese carried out in 2016-2017 a 180-day study with four subjects in a large-scale hybrid CELSS integrated experimental platform composed of four cabins and 15 subsystems which started with physico-chemical regeneration of air and water and gradually adding plants in the system (Tang et al. 2021). Subsequently, Lunar Palace 1 completed a technological upgrade, notaby with two plant cabins for a total planting area of 120 m^2 and a volume of 500 m^3, and the Lunar Palace 365 experiment with Earth-based closed human survival for a year took place between 2017 and 2018, with a material closure of over 98% (Fu et al.

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[352] Cf §4.2.2.

2021).

This is all the more reason why ESA plans to eventually build a ground technology demonstrator, namely the Facility for Integrated Planetary Exploration Simulation (FIPES) (Mas 2007), in which it is planned to test and demonstrate the feasibility of the as complete as possible closure of the MELiSSA loop, within a CH integrating humans (Figure 17).

Figure 17: Artist views of FIPES (Facility for Integrated Planetary Exploration Simulation). Credits: Definition study carried out by LIQUIFER Systems Group on behalf of ESA in 2006[353].

The infrastructures of the future ESA's ACE simulating facility will have to offer all the equipment and installations necessary to conduct simulation campaigns for manned space missions. Such simulation facility will enable the development, testing and validation of technologies associated with space habitats under the most realistic conditions possible (Figure 18, points 1 and 2). In other words, its ultimate goal is nothing other than to allow man to walk one day on Martian ground, while guaranteeing that the crew can return in a state of health close to that which they had at the beginning, despite the strong constraints described above. At the end of this section, we will examine the possibilities offered by a CH simulator to carry out purely terrestrial searches (Figure 18, point 3).

Within a truly 'high-fidelity' model, the preparation activities will allow the training of the crew, as well as the experimentation and optimisation of scientific protocols. These preliminary stages will have to take into account all the physiological, medical and psychological aspects, but also the technological ones (e.g. related to microtechnologies, cleantechs, information and communication technologies) specific to the extreme conditions in which the advanced LSS operates.

The construction of this human demonstrator will therefore allow the continuation of ESA's life support technology developments, in particular those involved in the adaptation and optimisation of operational procedures currently taking place in the MELiSSA Pilot Plant. Garcia-Gragera et al. (2021) reported on the current state of development of this facility and the most recent results of the integration work.

As a space analogue, such CH should allow the creation and application of conditions and environment comparable to space habitats.

Concretelly, the challenge is to design and then build a self-sufficient habitat housing a restricted group of humans, as well as organisms (bacteria, microalgae and higher plants, each originating from natural ecosystems) evolving within an ACE. The latter must be capable of the most complete possible (quasi

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[353] See project decription on LIQUIFER Systems Group website: https://liquifer.com/fipes/ (last retrieved on the 02.07.2020).

integral) recycling of air, water, food, as well as the various wastes produced by its operation. The design and development of this biological life support system must allow for the integration (or even the fusion) of various technologies necessary for its proper functioning, while ensuring the health of its organisms. It is expected that a crew of up to six people will be able to live in the facility for long periods of time (from a few weeks to several months or even years). In a nutshell, a facility such as FIPES would constitute a testbed to test and experiment the influence of drastic ecosystem conditions on humans and other ALSS organisms over particularly long periods of time, in near real-time and in a hyper-controlled manner.

Figure 18: Roles of FIPES.
FIPES represents ESA's possible future ground facility that could serve as a technology platform not only for 1) testing the mission in the most realistic conditions ('space analogue') and 2) validating and developing space technologies ('technology demonstrator'), but also for 3) conducting purely terrestrial research CH and 'ACE demonstrator' and 'CH demonstrator'). Credits: ESA.

In particular, it could bring together activities that are still distinct today, for example isolation simulation (Concordia station, underwater mission, work on offshore oil platforms, etc.) and the study of the effect of terrestrial confinement on the organism (outside of space constraints such as microgravity and radiation protection). This research laboratory could thus position itself as a unique analogue, without equivalent in Europe or even internationally, for the study of ACE and the showcase of the technological challenges of sending people to Mars.

FIPES could be built in a ten-year horizon in one of the ESA member countries still to be defined. It is an essential link in the development of a space mission that will perhaps step onto the ground of the red planet on the horizon 2035-2050.

It should also be noted that in the past, NASA has also looked into the development of such a facility (Henninger et al. 1996), without the projects materialising.

On the reasons why the perfect habitat – that fits all and every situation – has not been built yet', Häuplik-Meusburger & Bishop (2021) cited the few terrestrial analogues and orbital/transportation vehicles involving limited number of crew members (that are not representative of human beings) and limited duration, cultural differences for inhabitant acceptance of CH condition, as well as the need to address both individual and group processes[354].

In terms of activities, a CH that would integrate partial or complete ACE features, whether it is a ground demonstrator, a shuttle or a future Lunar or Martian base, must be used by its crew as a valuable support for:

- the implementation of scientific experiments and scientific protocols[355];
- the recycling of organic waste[356];
- the monitoring of the health of the crew members and the other ACE organisms[357];
- the routine medical care in case of illness, accident, etc.[358];
- the production, storage and preparation of food[359];
- the maintenance of medical and operational knowledge[360];
- the leisure activities (individual or in groups) and sports activities, in order to avoid monotony and to maintain the motivation of the crew members, who live in conditions of extreme isolation and confinement[361];
- the communication with assistance centers, families and relatives, and with the public (via social networks)[362];
- the operational and maintenance procedures[363];
- the optimisation of the habitability and the cleaning of the body, personal hygiene and cleaning of the habitat[364];
- possibly, the simulation of spacewalks (extra-habitat activities), in connection with aspects related to exobiology, but also to the management of pandemics[365].

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[354] Häuplik-Meusburger & Bishop 2021, pp. 180-181 (Box 7.1): '1. What we know is based on imperfect terrestrial analogues and a few orbital/transportation vehicles—all of which involve limited number of crew members and limited duration. Thus, our ability to generalize critical factors for a permanent ICE habitat intended to be occupied for extended durations (years) is almost nonexistent. 2. Only a few people that can report on outer-sphere experiences are available. All of them come from a small unrepresentative segment of human beings (e.g. well-educated, mainly male adults, little geographic or cultural diversity, etc.). 3. There are few existing opportunities to test new habitat designs in locations that are located in remote locations here on Earth (aka analogues) that are not already well established (aka settlements in polar regions or remote island chains). 4. All our perceived experiences are deeply entrenched in cultural practices. Cultural mindsets are powerful lenses that shape the desirability/acceptability of all things, including what we expect in our living spaces. Many of the existing analogues involve homogeneous participants from particular national or cultural groups. Thus, generalizability is severely restricted. What is acceptable for one group may be completely unacceptable to another. 5. There are both individual and group processes that must be addressed in designing functional, supportive facilities. These foci are highly interdependent but different. Fortunately, there also appears to be certain types of personalities that function best under the kinds of conditions found in ICE environments so we don't have to design for the entire gamut of human personality. 6. All the above mentioned are in interdependent and dynamically changing relationships.'

[355] Cf Annex A-§4.2.3.

[356] Cf Annex A-§7.4.

[357] Cf Annex A-§8.2.

[358] Cf Annex A-§8.2.7.

[359] Cf Annex A-§8.3.1.

[360] Cf Annex A-§9.4.

[361] Ibid.

[362] Ibid.

[363] Cf Annex A-§10.5.

[364] Ibid.

[365] Ibid.

Most of these activities will be discussed in the above-mentioned chapters of Oïkosmos Report as described above[366].

In conclusion, an ACE simulation facility such as FIPES is thus emerging not only relevant, but essential to demonstrate the technological feasibility of space analogue habitats operating in closed-loop.

6.1.2 The ACE demonstrator, a relevant laboratory for implementing non space R&D activities

In addition to its clearly stated space objective, a second component - terrestrial this time - will have the objectives, on the one hand, to carry out purely terrestrial R&D activities, and, on the other hand, to encourage the implementation of research synergies between actors (researchers, industrials, etc.) from the space and non-space sectors. These activities should allow the ACE demonstraor to offer a certain level of short-term return on investment, with direct terrestrial benefits from space exploration research.

It is possible to consider that the living conditions offered by future terrestrial habitats may become increasingly similar to those of space habitats in terms of 1) confinement, 2) isolation and autonomy, 3) environmental conditions to which inhabitants are exposed, 4) rationing of material and energy resources necessary for the habitat, 5) supply of nutrients necessary for the survival of the inhabitants and finally 6) due to increased compliance requirements for the environmental legislation and standards. For all these reasons, the ACE demonstrator, as a CH, is, furthermore, considered in this study as an illustration of a habitat under strong constraints. Obviously, it is not implied that this trend will one day actually bring the constraints of terrestrial habitats closer to the ones of space habitats. On the other hand, it is realistic to anticipate that an increasing number of tomorrow's habitats will be subject to one or more of them, for example during natural disasters and sanitary crisis such as pandemics.

Therefore, one of the objectives of this study is to demonstrate that in many respects, the construction of a scientific and technological infrastructure such as an ACE demonstrator seems relevant only from the perspective of its 'terrestrial' interest, as further discussed later[367]. In other words, a CH demonstrator has a strong intrinsic potential for an applied R&D questioning purely terrestrial issues, even independently of 'space' activities related to its primary mission of enabling human spaceflights for interplanetary exploration. For instance, long term exploration mission based on ACE shall facilitate a deeper understanding of the complex human-nature relationship for optimising health at the human-environmental interface, at the convergence of evolutionary psychology, environmentalism, evolutionary biology, and social economics (Seymour 2016).

In this perspective, the CH demonstration is useful to try to solve crucial problems both in space and on Earth. This research laboratory can serve as a catalyst for eco-innovation and a driver of technological development to question current terrestrial problems in areas as varied as ecotoxicology, recycling of organic materials and waste, optimal use of resources, biosafety and life in a confined environment.

In conclusion, the above-mentioned research synergies[368] could be placed at the core of ESA's science and technology programme on ALSS. Oïkosmos encompasses the terrestrial component of this program, which should make it possible to identify, encourage and maximise all forms of synergies between terrestrial and space research on ACE. The development of an ACE ground demonstrator

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[366] Cf §5.

[367] Cf §13 (technology empowerment of self-sufficient habitat on Earth) and §14 (contributions of ACE development to terrestrial sustainability).

[368] Listed in §5 and detailed in Annex A-Part II.

should be considered as a *sine qua non* condition for the optimal preparation of a Mars mission for which it represents the key terrestrial infrastructure. Moreover, this true technology platform would promote a continuous transfer of knowledge and technology from space to Earth and vice versa[369].

6.1.3 The ACE demonstrator as an experimental platform for exploring the concept of systemic sustainability

The ACE demonstrator is a relevant analogue ground facility to study and implement terrestrial sustainability, with environmental issues in its centre of gravity. It is tooled to deepen knowledge and develop solutions to mitigate of the depletion of material resources through resource recovery and valorisation. In particular, research in such an experimental platform is useful to explore the concept of 'systemic sustainability'[370].

According to Suomalainen (2012), it is possible to consider the ACE demonstrator as a 'sustainability laboratory'. In this respect, the combination of the organisms of the ACE within a CH form a model of an ideal 'sustainable system', capable of maintaining its survival and organisation away from its thermodynamic equilibrium, as envisaged by Ho & Ulanowicz (2005).

For this purpose, the ACE demonstrator should have a global evaluation reference system, based on appropriate criteria, making it possible to quantify the concrete effects of measures influencing the installation at the operational, environmental, energetic or technological levels. The performance of the integrated ACE could then be examined in a periodic, systematic and targeted manner. The definition of indicators for sustainability assessment and their monitoring over time would then be necessary to catalyse continuous improvement in its performance. In an attempt to analyse the sustainability of resource use, Suomalainen (2012) therefore proposed indicators to characterise bioregenerative LSS. These relate to 1) overall burden of the system in terms of materials and energy, 2) recycling and material use efficiency, 3) coverage time and need coverage level (dynamic indicators) and 4) resource and waste intensity indicators (expressing the amounts of resources needed and waste created). Through their meticulous and exhaustive monitoring, these valuable indicators that characterise the physico-chemical and biological conditions in presence also makes it possible to replicate precisely the experiments and ensure the reproducibility of their results.

Liu et al. (2021) considered typically the following indicators to evaluate the development and technological level of a space ACE: regeneration rate of oxygen, water and food (%); ALSS material closure (%); stability and reliability of the ALSS operation; energy consumption and space required for life support per person (kWh*m^3/person); weight of equipment required for life support (kg/person); labor intensity required for life support per person (hour/person).

With the above-described context, the activities of the ACE demonstrator enable the empirical and theoretical consolidation of the concept of systemic sustainability, as well as its modelling and testing, which in return allow the design of strategies on a larger scale, and thus contribute to the evolution of the industrial system towards sustainable development. Other contributions of ACE development to terrestrial sustainability will be discussed later in §14, and the sustainability facet for space ACE is further approached in §15.

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[369] Cf §9.

[370] Cf Annex A-§7.2.6.

6.2 Modalities of uses of an ACE demonstrator as a technological platform

An ACE demonstrator is not intended to be an exclusively academic project. The involvement of the economic world and society seems necessary for the long-term success of the Oïkosmos programme. The dual purpose of a CH simulator, at the convergence of terrestrial and space, should naturally position it as an 'open structure' for inter-institutional cooperation and exchanges with society.

In addition to its scientific interest, the third part of the Oïkosmos Report [371] envisages the ACE demonstrator as a technological platform capable of catalysing eco-innovation processes and accelerating the transfer of knowledge and technology related to ecosystems and CH. For example, it is a question of creating the conditions for the establishment of synergies between terrestrial and space-based research and the development of applications useful to society[372]. Annex A-Part III raises the following questions:

- What services could be offered to institutions and organisations wishing to conduct projects related to closed systems?
- How to finance the operational activities of an ACE demonstrator in the current context of relatively low research budgets in some European countries?
- How to involve communities of scientists, engineers, doctors, but also industrialists and innovation professionals traditionally evolving outside the space domain?
- How to build bridges between the many disciplines of the Oïkosmos research agenda while ensuring that collaborations and interactions of specialists from different backgrounds can be effective and productive in the long term?

Annex A-Part III outline possible answers to these questions, and conceptualise the different facets and modalities of using the ACE demonstrator as a technological platform for the various actors of the Research-Innovation-Market value chain (see Figure 19), in particular as:

- a flexible and dynamic facility allowing the mutualisation of physical resources[373];
- a Forum: a privileged place for the promotion of closed systems[374];
- a Competence centre: access to a complete expertise on closed systems[375];
- an Incubator: a catalyst for eco-innovation processes[376];
- an integrative platform promoting interdisciplinarity[377];
- an infrastructure to sustain research on closed systems[378];
- a project involving citizens through participatory science and open innovation[379];
- and provides final considerations[380].

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[371] Cf Annex A-Part III.

[372] Cf particularly §14.2.

[373] Cf Annex A-§12.

[374] Cf Annex A-§13.

[375] Cf Annex A-§14.

[376] Cf Annex A-§15.

[377] Cf Annex A-§16.

[378] Cf Annex A-§17.

[379] Cf Annex A-§18.

[380] Cf Annex A-§19.

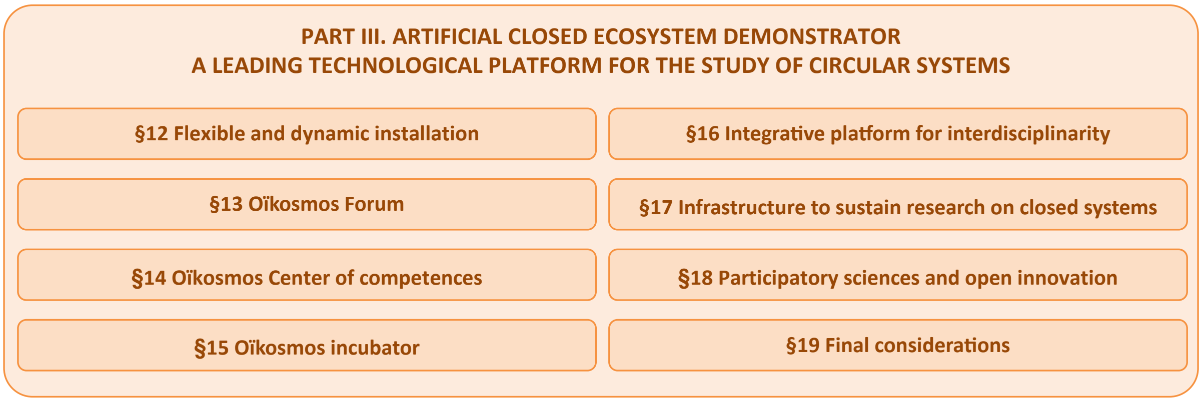

Figure 19: Part III of Oïkosmos Report [381].
An ACE demonstrator can be considered as a technological platform offering various opportunities for knowledge and technology transfer. The Part III of Oïkosmos Report [382] maps the multiple modalities of use, operational activities and services that a ground ACE simulating facility provides to the actors of the Research-Innovation-Market value chain.

It would therefore be a missed opportunity for space agencies such as ESA not to take advantage of building a structure open to interinstitutional cooperations in the form of such technological platform. Managed on a public-private and not-for-profit basis, the ground-based facility would be able to accommodate clients from academia (researchers) and industry. Eventually, the model discussed in Part III could be able to partially finance some of Oïkosmos' research activities. In particular, this would involve the mutualisation of the laboratory space and equipment available[383] or the provision of R&D services (feasibility studies, concept design, prototyping, intellectual property licences, etc.), through a multidisciplinary team of highly qualified experts in the technologies associated with ACE. Such a centre of competence on closed systems[384] could then profile itself as a 'one-stop-shop' for innovative companies and industries. In addition, the Oïkosmos Forum, composed of a Science-Society interface and a Science-Industry platform[385] would be inexpensive to set up, and potentially operational before the end of construction. In other words, the demonstrator is likely to offer a better cost/benefit ratio for society. Indeed, thanks to its stimulating conditions, it would accelerate the transfer of knowledge and technology related to the closed system, both by creating spin-offs that would be incubated nearby[386] or by supporting others that it would have attracted into what could become a Cluster on ACE[387].

As the cornerstone of the Oïkosmos programme, the ACE demonstrator could have a life of its own by offering spaces for promoting innovation, science and technology: conference and seminar rooms, exhibition halls, restaurants, etc. The gradual development of additional activities and of a network of skills through a forum, a competence centre and an incubator would make the simulator's environment - already technically favourable - conducive to exchanges of technological and commercial experience and practices, making it more than a series of ultramodern infrastructures adapted to the needs of its tenants, users and clients. A momentum could then form around the ACE demonstrator to compete for access, space, equipment and expertise around its technological platform, in the same way that physicists compete to use the few particle accelerators available, or astronomers compete for access to

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[381] Cf Annex A-Part III.
[382] Cf Annex A-§12 to §19.
[383] Cf Annex A-§12.
[384] Cf Annex A-§14.
[385] Cf Annex A-§13.
[386] Cf Annex A-§15.
[387] Cf Annex A-§17.

large-scale telescopes.

A thoughtful and balanced mix of researchers, specialists and experts collaborating at all levels of the ‘Research-Innovation-Market’ value chain would position the ACE demonstrator both as a driver of eco-innovation and as an amplifier of interactions and partnerships. In addition, it would represent a new kind of testbed and a formidable instrument for promoting the technological development of innovative applications and solutions. In the long term, it should become a technological showcase for ‘made in Europe’ applications at the convergence of space and terrestrial sectors.

Finally, an ACE demonstrator should be seen as a relevant technology platform to interface the terrestrial and space dimensions of LSS domain so that the development of one particular LSS component can act synergistically, as exemplified with a biomonitoring sensor[388].

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[388] Cf SUMIT projects in §9.

7 Consolidating the Swiss activities and rationale for ALSS and MELiSSA development (RO2.3, RO2.6.a, RO2.8.b)

A position paper on the 'consolidation of the Swiss activities and rationale for ALSS and MELiSSA development' (Besson & Erkman 2019), supported by UNIL rectorate, EPFL presidency and ESTEE and submitted to the Swiss Space Office, constitutes another research output on this dissertation (full report in Annex B1). In order to explore, map and assess Swiss activities, interests and strengths in LSS (RO2.3), the report aimed:

- to introduce the MELiSSA project and its connection with Swiss organisations[389];
- to map the space and terrestrial LSS and MELiSSA-related activities implemented in Switzerland[390];
- to assess the strengths of Swiss organisations in the context of LSS development and on the ongoing MELiSSA project[391];
- to explore the areas of interests for possible future collaboration opportunities in the field of LSS[392].

The document also encompassed a brief introduction to space ALSS and their relevance for terrestrial sustainability[393] as well as an analysis of the strengths, weaknesses, opportunities, threats (SWOT analysis) of the MELiSSA roadmap[394]. Finally, it presents the full results from the survey on Swiss activities, interests and strengths in ALSS[395] and provides the Facsimile of the Position Paper released in Spring 2019 by the MELiSSA industrial actors[396].

The Executive Summary of the position paper is available below in §7.1.

The position paper is also a component of the stakeholder engagement strategy[397] for consolidating the current Swiss activities and rationale for LSS and MELiSSA development into an active and productive cluster (RO2.6). This stakeholder engagement strategy aims at 1) widening the base of the existing diverse community (academia and industry) by bringing in new actors traditionally not yet involved in the ALSS research, and 2) preparing the ground for a stakeholder engagement strategy in the field of ALSS as an input for establishing a long-term view of Life Support technologies to be developed in Europe. The related research outcomes are: BELiSSIMA Phase A (RO2.6.b (as well as RO2.4)[398] and the proceedings of the ESA Closed Habitat Forum 2016 (RO.2.6.c (as well as RO2.8.c))[399].

Moreover, the position paper is also one of the research outputs that fosters the institutional dynamics for ACE and LSS development in Switzerland and promote related education and communication activities (RO2.8)[400]. At educational and communication levels, pursuing the current momentum on space and terrestrial ALSS-related activities in Switzerland[401] - especially within the MELiSSA

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[389] Cf Annex B1-§1.3.
[390] Cf Annex B1-§1.2, 1.4 and Annex B-§2.1.
[391] Cf Annex B1-§2.1.
[392] Cf Annex B1-§2.1.
[393] Cf Annex B1-§2.2.
[394] Cf Annex B1-§2.3.
[395] Cf Annex B1-§2.4.
[396] Cf Annex B1-§2.5.
[397] Cf §10.
[398] Cf short project description in §8.1, and more particularly its technical note TN.118.1.6 (Annex C2).
[399] Cf short project description in §10.1.
[400] Cf §12.
[401] Cf Annex B1-§2.1.5.3 and §2.1.5.4.

framework - could notably aim at:

- Raising public awareness of the spin-off potential of investments in space exploration (e.g. space applications for socioeconomic development, closed-loop systems and sustainable resource management) through a sustained promotion/communications campaign;
- Using the inspirational nature of ALSS and CH to encourage a new generation of scientists and engineers and to contribute to the emergence of new fields of research;
- Strengthening interdisciplinary research for space exploration and fostering high quality academic publications;
- Engaging students in funding challenges for innovators to work on the key items which need to be developed to enable ALSS and CH for space applications.
- Identifying additional scientific and technical research of common space/non-space interest and increase awareness of the downstream added-value chains benefiting society;
- Strengthening the position of organizations such as UNIL, EPFL, ETHZ, EAWAG, CSEM and HEI (HES-SO//Valais-Wallis) and ESTEE as key members/partners of the MELiSSA project;
- Federating other stakeholders to become active members, thus furtherly extending the community with actors such as private organizations (SMEs, start-ups, etc.) - should the latter be originally space-driven or not - or university hospitals;
- In the framework of STEM disciplines-related activities, using the high MELiSSA attraction pool for environment, ecology, high tech education and societal behaviour;
- Incentivizing Swiss non-space industry to engage in space ALSS activities and with ESA;
- Diversifying and broadening Swiss space stakeholders and ESA’s user-base and engagement with the private sector;
- Facilitating the elaboration of concrete projects proposals of joint terrestrial and space interest;
- Taking benefit from the strong potential of ALSS for sustainability research and applications;
- Exploiting synergies between research in space and on Earth to enhance the benefits of space exploration for society and to leverage on terrestrial research for space.

Activities related to education and communication should aim at:

- Supporting the organisation of a (bi-)yearly targeted workshop that would respond to the demand of Swiss parties for increased interactions between MELiSSA activities and Swiss ALSS stakeholders. Such workshop would enable MELiSSA community to provide an overall activity report – not specific to Switzerland. Conversely, a summary of new Swiss ALSS development would be shared. This would build an essential communication channel to circulate information from the complementary activities distributed within the overall community.
    - Consequently, such targeted workshop would would:
        - facilitate the definition of topics of investigation;
        - legitimate working groups (including ESA ones);
        - secure long-term roles;
        - exchange best practices and lessons learned;
        - facilitate technology transfers and spin-in & spin-out entities creation
        - enable innovative ground demonstration and mission concepts;
        - contribute to sustainability of space;
        - close knowledge gaps.
- Allowing an increased swiss visibility at the International level of manned space exploration.

Finally, the Position paper was presented during the MELiSSA conference 2020[402]. The discussed presentation did not only focus on fostering MELiSSA projects within Switzerland, but also on facilitating the emulation of such Position Paper on ALSS in other European countries.

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[402] Cf abstract in Annex B2a and presentation in Annex B2b.

7.1 Executive summary

With this Position Paper, the Swiss stakeholders active in the field of Advanced Life Support Systems (ALSS), including those directly involved in the R&D and technology transfer of related space and Earth-based solutions, would like to express their strong interest in the ongoing Micro-Ecological Life Support System Alternative (MELiSSA) project of the European Space Agency (ESA).

In the context of the preparation of the forthcoming ESA Ministerial Council Space19+, the overall objectives of this Swiss Position Paper are: (a) To develop an ALSS roadmap, encompassing the three main pillars of the Swiss Space Policy and (b) To demonstrate that the development of the field of ALSS would benefit from a consolidated and concerted effort from the Swiss stakeholders, especially within the framework of ESA's MELiSSA project.

The Swiss MELiSSA and ALSS stakeholders encompass a broad range of public and private organisations and can be considered as a cluster offering a wide spectrum of complementary scientific and technological skills and know-how. With almost thirty organisations involved and more than seventy people active in ALSS activities at the national level, it appears that the emerging and dynamic community in the field of ALSS has reached a critical size and momentum in Switzerland – and in Europe as well.

According to the conclusions of a survey on Swiss activities, interests and strengths in ALSS, the Swiss ALSS community has recently gained a clear perception of the assets and uniqueness of MELiSSA and is now demonstrating a precise understanding on the future kinds of and topics for collaboration. The active participation of the community can be demonstrated by more than 30 R&D and technology transfer projects, covering most of the dimensions and topics of investigations on ALSS. Moreover, a growing number of Swiss public organisations and private companies have expressed their willingness to be engaged further and the potential of increasing scientific and technical collaborations is significant.

As stated by most of the key Swiss players in the field of ALSS, a resolute and continued financial support for MELiSSA activities should remain within ESA. Concretely, and as evidenced in the past notably for flight experiments, the best way would be to continue financing the MELiSSA activities via the ESA Exploration programmes – currently European Exploration Envelope Programme (E3P)[403] – for the next periods (Period 2 and beyond) which should aim at:

- Maintaining a steady flow of collaborative partnerships, including non-space academic institutions and industry to engage in space activities and with ESA (spin-ins and spin-outs);
- Securing the continuity of MELiSSA technology developments in Life Support for space exploration, sustained by a robust roadmap and associated projects in the E3P programme;
- Positioning the Swiss space ecosystem at the cutting edge of the ALSS developments by delivering In Orbit Demonstrator (IOD) of building blocks (such as photobioreactors) paving the way for a credible approach towards a human settlement on the Moon, on Mars or in other space stations developed in the solar system;
- Enabling a faster and bigger access to international manned space exploration activities.

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[403] More information on E3P and Human Spaceflight and Robotic Exploration Programmes on ESA website: https://www.esa.int/About_Us/Ministerial_Council_2016/Human_Spaceflight_and_Robotic_Exploration_Programmes (last retrieved on 08.08.2019).

The Swiss space and terrestrial ALSS communities are also looking towards a political support with a long-term vision and planning, with adequate funding, aiming at:

- Investigating topics relevant both for human space exploration and for their associated Earth-based applications;
- Attracting and increasing engagement of the Swiss non-space ALSS organisations (including industries) in space exploration;
- Fostering synergies between Swiss players and the MELiSSA community in order to combine their complementary skills in a concerted effort within a stable project framework;
- Further considering developing a dedicated testbed in Switzerland to experiment ALSS concept in a short to mid-term perspective, as expressed by most of the Position Paper's survey respondents;
- Leveraging on Swiss expertise in R&D, technology cooperation and transfer opportunities to better exploit ALSS knowledge and know-how for space exploration and contribute to the development of terrestrial applications beneficial to society (spin-out activities);
- Supporting the organisation of a (bi-)yearly targeted workshop that would respond to the demand of Swiss parties for increased interactions between MELiSSA activities and Swiss ALSS stakeholders. Such workshop would enable MELiSSA community to provide an overall activity report—not specific to Switzerland. Conversely, a summary of new Swiss ALSS development would be shared. This would build an essential communication channel to circulate information from the complementary activities distributed within the overall community.

In conclusion, this Position Paper shows evidence that the current timing appears highly adequate for:

- Consolidating the Swiss activities and rationale for ALSS into an active and productive cluster during the next E3P period;
- Positioning Switzerland as a key player in space and terrestrial ALSS and with a strong potential for increasing the developments and collaborations within the MELiSSA project;
- Allowing an increased international visibility for Switzerland in the field of manned space exploration, as well as for a reliable and efficient circular economy.

Therefore, for the next E3P periods, the authors, along with the organisations endorsing this Position Paper[404], recommend that ALSS and MELiSSA R&D and technology transfer activities in Switzerland should continue to benefit from a stable and long-term programmatic framework with corresponding funding.

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[404] Cf Impressum on p. 2 and signatures on p. 17 in Annex B1

8 BELiSSIMA Phase A as a concrete R&D project demonstrating terrestrial and space research synergy potential (RO2.4, RO2.6.b)

In order to demonstrate the terrestrial and space research synergy potential through the elaboration and consecutive implementation of a concrete R&D project (spin-in or spin-out) (RO2.4), this work encompasses the BELiSSIMA project as an example of research output related to spin-out R&D on ACE.

At ESA level, and in order to complete the picture of space-related R&D activities focusing on material loop closure - such as those in progress at the MELiSSA Pilot Plant – the BELiSSIMA project can be seen as a typical example of what could be an enabling factor to foster the convergence between space and terrestrial community working on applied R&D and technology transfer in the field of water recycling, micropollutant behaviour monitoring and food production. Therefore, such ACEs could, for example, be used to observe the effects of various microcompounds (such as endocrine disruptors, biocides, etc.) and trace elements on several categories of species under test conditions that are more realistic than those of a laboratory.

Section 8.1 provides a short description of the Phase A of the BELiSSIMA project. The following documents[405] are annexed:

- BELiSSIMA Phase A - Detailed proposal AO/1-8342/15/NL/AT[406];
- MELiSSA Technical note TN 118.1.4 - Review of terrestrial closed ecosystems studies[407]:
    - Review on novel, sustainable concepts – Industrial ecology and closed habitats[408]:
        - Industrial ecology and metabolism[409];
        - Eco-industrial parks[410];
        - Circular economy[411];
        - Biorefinery[412];
        - Closed habitats[413].
    - Review on terrestrial life support systems - Biospheres[414]:
        - Artificial closed ecosystems[415];
        - Life support systems[416];
        - Biospheres[417].
    - Major challenges and knowledge gaps[418]:
        - General conclusions[419];
        - Industrial ecology and metabolism; eco-industrial parks; circular economy[420]:

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[405] The below-listed sections of Annexes C1-C2a-C2b-C2c, introduced in §8, were prepared by ESTEE, mainly by Théodore Besson (Annex C2a and Annex C2b, and support to Annex 2c), and Dr. Petros Dimitriou-Christidis (Annex C2c prepared with VITO), with the support of Sébastien Lavanchy (Annex 2b).

[406] Cf Annex C1.

[407] Cf Annex C2a, pp. 40-74.

[408] Cf Annex C2a-§7.

[409] Cf Annex C2a-§7.1.

[410] Cf Annex C2a-§7.2.

[411] Cf Annex C2a-§7.3.

[412] Cf Annex C2a-§7.4.

[413] Cf Annex C2a-§7.5.

[414] Cf Annex C2a-§8.

[415] Cf Annex C2a-§8.1.

[416] Cf Annex C2a-§8.2.

[417] Cf Annex C2a-§8.3

[418] Cf Annex C2a-§9.

[419] Cf Annex C2a-§9.1.

[420] Cf Annex C2a-§9.2.

            - Industrial ecology assessment of BELiSSIMA bioprocesses[421].
        - Biorefinery[422]:
            - Adaptation of relevant biological processes of space regenerative life support systems to terrestrial biorefineries[423].
        - Closed habitats; artificial closed ecosystems; biospheres[424]:
            - Decentralization and down-scaling to small wastewater treatment units and applications to closed and confined systems[425];
            - Investigations on closed habitat exposome based on the down-scaling of urban farming and wastewater valorization technologies to habitat scale (Annex C2a-§9.4.2).
- MELiSSA Technical note TN 118.1.6 - Development of a stakeholder engagement strategy[426]:
    - Task 1.6 Development of stakeholder engagement strategy (Annex C2b-§4):
        - Expected outcomes[427];
        - Identification of stakeholders[428];
        - Stakeholders analysis [429] : stakeholders segmentation; stakeholders prioritization; selected R&D Topics group/ High priority topics; stakeholder distribution.
        - Kinds of collaboration [430] : private organizations; public/ International organizations & foundations/ NGOs; academic/ Applied R&D/ Innovation organizations; professional Associations & Networks.
        - SWOT analysis[431];
        - Implementation of the engagement strategy (Task 2.1-2.2)[432]; wave 1 contacts; wave 2 contacts; scope overview; workshops.
        - Stakeholder engagement success criteria[433].
    - Annex: reference documents[434].
- MELiSSA Technical note TN 118.2 - The future of BELISSIMA: roadmap and recommended Frame of Work[435]:
    - Interaction with stakeholders[436]: individual stakeholders[437].
    - Frame of Work: funding channels[438]: European funding[439]; National funding channels with potential involvement of other countries[440]: Switzerland[441].

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[421] Cf Annex C2a-§9.2.1.
[422] Cf Annex C2a-§9.3.
[423] Cf Annex C2a-§9.3.1.
[424] Cf Annex C2a-§9.4.
[425] Cf Annex C2a-§9.4.1.
[426] Cf Annex C2b, pp. 7-27 and annexes.
[427] Cf Annex C2b-§4.1.
[428] Cf Annex C2b-§4.2.
[429] Cf Annex C2b-§4.3.
[430] Cf Annex C2b-§4.4.
[431] Cf Annex C2b-§4.5.
[432] Cf Annex C2b-§4.6.
[433] Cf Annex C2b-§4.7.
[434] Cf Annex C2b-§5.
[435] Cf Annex C2a.
[436] Cf Annex C2a.
[437] Cf Annex C2c-§4.1.
[438] Cf Annex C2c-§5.
[439] Cf Annex C2c-§5.1.
[440] Cf Annex C2c-§5.2.
[441] Cf Annex C2c-§5.2.1.

- BELISSIMA roadmap[442]:
    - Short- to mid-term strategy for BELISSIMA activities[443];
    - Revision of long-term strategy for BELISSIMA activities[444];
    - Scientific/technological views[445];
    - Programmatic aspects of BELISSIMA activities[446].
- Project risk assessment[447]:
    - Construction of the project risk assessment table[448];
    - Discussion of the project risk assessment table[449].

The author of this thesis elaborated the vast majority of the ESTEE content in the above project documents (TN 118.2 excluded), all written in the context of his PhD study, so that the BELiSSIMA technical notes TN 118.1.4 and TN 118.1.6 are considered as research outputs.

BELiSSIMA Phase A Technical Note 118.1.6 is notably a component of the stakeholder engagement strategy[450] for consolidating the current Swiss activities and rationale for LSS and MELiSSA development into an active and productive cluster (RO2.6.b). This stakeholder engagement strategy aims at 1) widening the base of the existing diverse community (academia and industry) by bringing in new actors traditionally not yet involved in the ALSS research, and 2) preparing the ground for a stakeholder engagement strategy in the field of ALSS as an input for establishing a long-term view of Life Support technologies to be developed in Europe. The related research outcomes are: Position Paper - Consolidating the Swiss activities and rationale for ALSS and MELiSSA development (RO2.2, RO2.6.a and RO2.8.b)[451], and the proceedings of the ESA Closed Habitat Forum 2016 (RO2.6.c, RO2.8.c and RO3.2)[452].

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[442] Cf Annex C2c-§6.

[443] Cf Annex C2c-§6.1.

[444] Cf Annex C2c-§6.2.

[445] Cf Annex C2c-§6.3.

[446] Cf Annex C2c-§6.4.

[447] Cf Annex C2c-§7.

[448] Cf Annex C2c-§7.1.

[449] Cf Annex C2c-§7.2.

[450] Cf §11.

[451] Cf Executive summary in §7.1; Annex B1.

[452] Cf short project description in §10.1.

8.1 Short project description

Project title: BELISSIMA – Phase A (AO/1-8342/15/NL/AT)

Project scope: Behaviour and effects of microcompounds in closed soil-free ecosystems

Client: ESA

Partners: VITO (prime contractor), ESTEE, UNIL and UGent (subcontractors)

Dates: 2016-2019

BELISSIMA was a preparatory project leading to a research project on the behaviour, fate, and effects of microcompounds in the ESA's MELiSSA loop. Microcompounds are chemicals of emerging concern that are typically difficult to analyse and characterise due to their trace concentrations, ubiquity, diverse chemical structures, diverse modes of toxicity, and largely unknown types of interactions in which they engage. Similar to natural ecosystems, insights into microcompound behaviour and effects in the MELiSSA loop are largely unknown. However, the loop's short cycle times and small buffer volumes make it an interesting platform for studying microcompound behaviour, fate, and effects on ecosystems under accelerated conditions. The BELiSSIMA hardware provides a small-scale model of natural or engineered systems in which non-target screening models can be tested and validated. Knowledge from the BELISSIMA project on the MELiSSA loop processes can be applied to analogous terrestrial processes, e.g. those involving treatment of waste, resource recovery, decentralised water treatment, and efficient and safe food production.

✧ *Key aspects*

Scope: behaviour and effects of microcompounds in closed soil-free ecosystems, behaviour and impact of microcompounds, closed system chemical contaminants, microcompound removal, water reuse/ recycling.

Topics of investigation: 1) Microcompound behaviour (technology development for monitoring of microcompounds; Investigation of behaviour of microcompounds and of micro-organisms); 2) Water reuse/recycling (Technology development for recycling, removal, retention and/or degradation of microcompounds, as well as for nutrient separation/recovery; adaptation of closed system bioprocesses to biorefineries); 3) Investigation of behaviour of microcompounds in food production using water recovered nutrients.

Societal challenges: ecotoxicology.

It is clear that synergies and common research interests exist between the BELISSIMA project and terrestrial research on water loop closure and organic waste recycling. These synergies can be summarised as follows:

- Developing and implementing sound evaluation and monitoring tools;
- understanding and predicting their fate mechanisms;
- understanding their impact on structure and/or function of aquatic ecosystems;
- understanding their fate and effects in all relevant environmental compartment;
- understanding the risks they pose and developing safety abatement measures; and
- promoting societal discussion on reducing their concentrations in environment.

Within the BELISSIMA project, and in addition to the elaboration of the technical notes, ESTEE had the following roles:

- Provide a database of relevant Swiss and European stakeholders in science, technology, and regulatory affairs in the fields of water/wastewater management, food production, and air purification;
- Provide an interface between the project and important Swiss stakeholders with which ESTEE has strong connections;
- Provide technical expertise and guidance in defining the project scope, scientific questions, and research objectives;
- Perform project planning, management, and execution;
- Provide a test bed for the experimental evaluation of microcompound fate, behaviour, and effects in its Scorpius closed-loop prototype;
- Accelerate transfer and commercialisation of technologies developed within the project.

At the end of this BELISSIMA Phase A project, a roadmap and frame of work was recommended, including possible funding channels and the programmatic aspects for future BELiSSIMA activities.

- Interaction with stakeholders[453];
- Frame of Work: funding channels[454];
- BELISSIMA roadmap[455];
- Project risk assessment[456].

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[453] Cf Annex C2a.

[454] Cf Annex C2c-§5.

[455] Cf Annex C2c-§6.

[456] Cf Annex C2c-§7.

9 Co-development technology roadmap for LSS development (RO2.5)[457]

Space technologies often ‘spin-out’ or ‘trickle down’ to Earth applications. The reduction of the technology readiness level (TRL) of a space technology is the removal of requirements dictated only by flight and space-mission conditions, which are not encountered on Earth. These requirements are not necessary to be met for a technology to perform properly on Earth. Specifically, this reduction involves the adaptation of a space technology with a high TRL (above 6) to a terrestrial variant with a lower TRL (below 6). This reduction is essential for the increase of the mass appeal and marketability of a technology, due to its higher affordability and lower complexity for applications relevant to ground environments.

There are countless examples of ‘reduced’ space technologies that have spun out to terrestrial applications, including those in the areas of computing, imaging, navigation, and medical devices. Most of the space-oriented technologies developed as part of life-support systems have the potential for spin out[458].

For ALSS, even though such spin-out process is possible, co-development for Earth and Space with usually common requirements can happen, typically until TRL 5. Then, above TRL 5, space and terrestrial development are following different technological trajectories.

Over the years, MELiSSA has become a strong and well-supported project. Management challenges include convincing investors for the long-term space LSS development (years to decades). This immense challenge is supported by an enormous terrestrial interest. The co-development through space and terrestrial roadmap and collaboration should give the opportunity to build new markets related to Earth-based applications, with products that customers will pay for. In return, the R&D could be financed through terrestrial royalties.

One example of spin-out is the Biostyr nitrification technology, which was originally co-developed by MELiSSA and Veolia, and is currently marketed by Veolia in Europe for use in wastewater treatment plants[459]. It should be noted that apart from spin-out, a ‘spin-in’ phenomenon is observed, in which, naturally, terrestrial technologies are adapted for use in space. Nitrification of urine also constitutes an example of a spin-in technology, which, having been originally developed for terrestrial applications, is currently adapted for use in life support systems in space.

Also, it should be mentioned that some technologies can undergo an iteration of successive/parallel spin-in and spin-out - and reversely - during their specific technological development, including in the framework of space and terrestrial life-support system development.

The emerging Swiss community on ALSS addresses both directions of these spin-in and spin-out pathways, thanks to its innovation ecosystem in place.

With the aim to illustrate a possible co-development technology roadmap with an exemplifying prototyping project (RO2.5), this section encloses several research outputs related to the SUMIT projects developed by ESTEE in collaboration with CSEM. SUMIT stands both for Space Urinalysis Module for Innovative Toilet (spin-in) and for Smart Urinalysis Module for Innovative Toilet (spin-out). The SUMIT roadmap considers that the biomonitoring component of an ALSS loop using miniaturised

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[457] Related research outputs:
- The synergistic approach of the research on ACE is introduced in §5.1;
- The vast majority of the content of Annexes D1-D2-D3 – summarised in §9.1, §9.2 and §9.3 – were drafted by ESTEE, mainly by Dr. Petros Dimitriou-Christidis, with the support of Théodore Besson.

[458] Cf §14.2.

[459] Biostyr™ on Veolia website: https://www.veoliawatertechnologies.com/en/products/biostyr (last retrieved on 09.07.2021).

sensors for has a clear potential both for spin-in and spin-out pathways.

In each case, while progressing in parallel and separately sometimes for long period, such co-development benefits from reciprocal spin-in and/or spin-out pathways, leading to period of intense cross-fertilisations. Such co-development notably involves eco-innovation processes such as technological transfer that can consolidate, transform and scale into another form of value proposition specific to the context of the other side of co-development.

Three SUMIT research outputs are introduced afterwards:

- Development of SUMIT (Space Urinalysis Module for Innovative Toilet): Crew health monitoring and support of ALSS functionality (§9.1; Mesures de Positionnement (MdP) - Call for Proposals 2020: full proposal in Annex D1);
- Health Monitoring Toilet[460] (§9.2; Innocheque technical report: full proposal in Annex D2);
- SUMIT - Smart Urinalysis Module for an Innovative Toilet[461] (§9.3; Innosuisse application: full proposal in Annex D3).

Annexes D1, D2 and D3 are to be considered as confidential.

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[460] 703-CT.2035, Innosuisse Voucher 49466.1 INNO-ENG.

[461] Innosuisse application - Impulse Programme innoCH - 55059.1 IP-ENG.

9.1 Development of SUMIT (Space Urinalysis Module for Innovative Toilet): Crew health monitoring and support of ALSS functionality

ESTEE, in collaboration with CSEM, applied to the Call for proposals 2020 'Mesure de Positionnement to promote Swiss competences related to space activities, initiated by the Swiss Space Office of the State Secretariat for Education, Research and Innovation (SERI/SSO). The proposal[462] entitled 'Development of SUMIT (Space Urinalysis Module for Innovative Toilet): Crew health monitoring and support of ALSS functionality', aims at incorporating a urine biomarker monitoring component in a space toilet, having implications for both crew health and advanced life support systems (ALSS).

The proposed SUMIT prototype will be created as a space product for incorporation into a space toilet (e.g. in the International Space Station or a planetary settlement). At the same time, the prototype can be incorporated into terrestrial urine-separating toilets, which have an important function in sustainably recovering water and nutrients from urine. Therefore, SUMIT also has applications in terrestrial waste treatment decentralisation schemes, as well as in non-invasive and personalised medical care approaches.

The project will promote the collaboration between Swiss industrial and academic partners (ESTEE and CSEM), companies with strong business and technical interest and competences in the development of space technologies.

The project would better position ESTEE and CSEM, as core members of an extended consortium of primarily Swiss stakeholders, to proceed with the further development and commercialisation of the proposed SUMIT prototype through a competitive ESA program, such as the ESA Integrated Applications Promotion (IAP) program.

✧ *Brief description of the study*[463]

Although there is currently no routine monitoring of any biomarkers in space, this is expected to change soon, as upcoming long-haul space missions will have to rely less on support from Earth. The scope of the proposed study is the development of the SUMIT (Space Urinalysis Module for Innovative Toilet) prototype (TRL 4) that can be incorporated into a space toilet (e.g. in the International Space Station or at a planetary base). SUMIT will accurately and automatically monitor different biomarkers in fresh urine, an ideal medium for biomarker monitoring. Up to four biomarkers will be measured using miniaturised electrochemical sensors. These will initially include pH and glucose. In a later stage of the study, two additional biomarkers will be incorporated (a choice from urea, calcium, sodium, potassium, chloride, and lactate). SUMIT will be useful not only for the non-invasive monitoring of crew health, but also for the overall functionality of advanced life support system (ALSS) (e.g. regulation of the urine loading to a downstream nitrification process, proper nutrition of food plants, prevention of scaling in water recovery processes, etc.).

The main tasks of the study will involve development of: space-driven design criteria and requirements; fluidic components, including interfacing with space toilet; sensor array; calibration system; and sensor reading and data communication. The study will be carried out in collaboration between CSEM and ESTEE (the academic and industrial partner, respectively), two Swiss companies with strong business and technical interest and competences in the development of space technologies.

At the end of the MdP study, the SUMIT prototype will better position the CSEM and ESTEE team, together with other stakeholders, to apply for an ESA grant (e.g. through the ESA Integrated Applications

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[462] Cf Annex D1 (confidential).

[463] Cf Annex D1-§1.4.

Promotion program), to further develop SUMIT, and eventually valorise its technologies into terrestrial sustainability applications.

✧ *Novel and innovative sensors*[464]

The SUMIT prototype proposed in this study will use a limited range of printable electrochemical sensors, capable of monitoring a few important urine biomarkers. However, as electrochemical sensors are a very active area of R&D at CSEM, the development and incorporation of novel and innovative sensors will be pursued. For example, beyond the macronutrients proposed as urine biomarkers in this proposal, micronutrients (i.e. vitamins and minerals) are also important biomarkers, as they are also essential to health at every stage of life; and their deficiencies, insufficiencies, or overconsumption are associated with an increased incidence of various pathophysiological states and poor quality of life (Höller et al. 2018). Another example of novel and innovative sensors envisages the use of recently discovered nanoscale extracellular vesicles called exosomes. Urinary exosomes have attracted significant interest as a new source of early biomarkers for the early screening of bladder cancer (Woo et al. 2017). As our prototype will be designed to operate with sensor cartridges for easy sensor installation and replacement, novel sensors will easily be incorporated into the prototype, with limited hardware and firmware adjustments.

✧ *Technical part of the proposal*

The general requirements for biosensors in space, recently delineated by Roda et al (Roda et al. 2018), are directly applicable to the development of our urinalysis module. Based on the latter, the design criteria for the urinalysis module[465] are:

- Quantitative analysis;
- Minimal sample pretreatment;
- Simple (or automated) operation;
- Intuitive communication/interpretation of results;
- Minimal resource consumption, in terms of mass, volume, electrical power, and consumables;
- Maximal reusability, and minimal waste generation;
- Reconfigurable and modular construction;
- Operation in microgravity;
- Long shelf life of device and consumables and minimal need for refrigeration;
- Safety, including multi-level containment and safe disposal;
- Data personalization and privacy (added specifically to the above-list).

The technical part of the proposal is composed of the following sections:

- Motivation for pursuing the proposed project[466]:
    - Urine as an ideal source of crew health biomarkers[467];
    - Urine biomarker monitoring and crew health[468];
    - Urine biomarker monitoring and ALSS functionality[469]:

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[464] Cf Annex D1-§1.5.1.1.

[465] Cf Annex D1-§2.2.1.

[466] Cf Annex D1-§2.1.

[467] Cf Annex D1-§2.1.1.

[468] Cf Annex D1-§2.1.2.

[469] Cf Annex D1-§2.1.3.

    - Urine processing[470];
    - Crop production[471];
    - Other applications in ALSS and space exploration[472].
  - State of the art in space urine biomarker monitoring[473].
- Technical description of the study[474]:
  - Design criteria for the urinalysis module[475];
  - Technological readiness level (TRL) aim of the urinalysis module[476];
  - SUMIT prototype main components and functions[477].
- Technical and/or scientific approaches selected[478];
- Study plan logic with a clear link between the academic and industrial partners[479];
- Work breakdown structure[480].

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[470] Cf Annex D1-§2.1.3.1.

[471] Cf Annex D1-§2.1.3.2.

[472] Cf Annex D1-§2.1.3.3.

[473] Cf Annex D1-§2.1.4.

[474] Cf Annex D1-§2.2.

[475] Cf Annex D1-§2.2.1.

[476] Cf Annex D1-§2.2.2.

[477] Cf Annex D1-§2.2.3.

[478] Cf Annex D1-§2.3.

[479] Cf Annex D1-§2.4.

[480] Cf Annex D1-§2.5.

9.2 Innocheque technical report - Health monitoring toilet

The goal of an Innosuisse innovation cheque is to offer SMEs trial working with research partners and test the feasibility of their idea.

The innovation project implemented by ESTEE and CSEM in 2020-2021, entitled ‘Health Monitoring Toilet’, was granted by Innosuisse[481]. Its innovative idea is a stand-alone urine biomarker measurement module that can be connected as an add-on to any sitting toilet. Such product will enable the quantitative, accurate and affordable monitoring of urine biomarkers in a non-invasive, hygienic, user-friendly and decentralised manner.

Tasks/questions addressed in the project were:

- Definition of 1-2 concepts of automated microfluidic setups with embedded reagents for biosensing, including sensor calibration;
- Development of technical requirements, specifications, and workflow (from sample preparation to readout to data exploitation);
- Evaluation/ranking of the feasibility of specifications, development effort, system footprint, disposables, and costs;
- Design support in the integration of the concept into a toilet;
- Development of the scientific and technical approach for future development and commercialisation.

While elaborating the above-mentioned points, ESTEE and CSEM also applied to get the following grant from Innosuisse, as described in the next section.

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[481] 703-CT.2035 Innosuisse Voucher 49466.1 INNO-ENG: full technical report in Annex D2 (confidential).

9.3 SUMIT - Smart Urinalysis Module for an Innovative Toilet

ESTEE and CSEM then applied to Innosuisse Impulse Programme innoCH[482] as a follow-up project from Innocheque[483]. Approved in June 2021, the project started in September 2021.

The full proposal compiles the following topics[484]:

- Value creation in Switzerland: business model and value proposition; target value chain position; competitive situation, USP (unique selling proposition); market size; planned revenue and profitability development; potential customers; customer model; market access and marketing approach; implementation plan; and ecological or social impact: health and quality of life; maximising local/CH resources; contributions to the circular economy.
- Solution: novelty of the solution; state of science and technology; quantifiable goals to reach; already performed preliminary work.
- Project partners;
- Intellectual property rights;
- Project planning;
- Financial plan;
- Business plan for the SUMIT project[485].

⟡ *Executive summary*

The aim of the project is the development of the Smart Urinalysis Module for an Innovative Toilet prototype, a mobile health (mHealth) wellness/lifestyle device and app for the home-based monitoring of biomarkers in a user's urine directly from the toilet. While mHealth technologies have increased the possibilities of continuous monitoring of physical parameters, still little is possible for monitoring important biological fluids, as urine, at home.

SUMIT will initially measure the following urine biomarkers: pH, glucose, and sodium ions (Na+), as these provide information about various physiological parameters related to diet, hydration, metabolism, fitness, and organ function.

Three products will be sold as part of the SUMIT package:

- Toilet add-on device: automatic sample collection and processing; readout; data transmission;
- Disposable sensor cartridges: multiparameter urine analysis;
- Mobile app: user Interface and data communication.

The following distinct consumer segments will be targeted:

- 18-34 year-old fitness enthusiasts with an app for everything;
- 35-54 year-old parents, who put their children's health first;
- 55+ people who want care close to home.

The project consortium is formed by: Earth Space Technical Ecosystem Enterprises (ESTEE), CSEM &

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[482] Innosuisse application - Impulse Programme innoCH: SUMIT - Smart Urinalysis Module for an Innovative Toilet (55059.1 IP-ENG): full proposal in Annex D3 (confidential).

[483] Cf §9.2.

[484] Cf Annex-D3a.

[485] Cf Annex D3b.

EPFL+ECAL Lab. Each partner brings individual key core expertise to overcome the technical challenges, validate the solution and evaluate its acceptance.

ESTEE plans to launch its SUMIT products by 2024 and expects to sell about 14’000 devices, 300’000 cartridges, and 24’000 monthly subscriptions per year in 2027. In addition, the project is expected to create within ESTEE from 6 qualified jobs in 2024 to 14 qualified positions in 2027.

During prototype and product development, feedback will be received by SIAMP, a leader in the development and production of toilet components. Feedback regarding data interpretation and applications will also be received by Haute Ecole de la Santé La Source.

10 Stakeholder engagement strategy for consolidating the current LSS and MELiSSA development (RO2.6)

To elaborate a stakeholder engagement strategy for consolidating the current Swiss activities and rationale for LSS and MELiSSA development into an active and productive cluster (RO2.6), this thesis encompasses activities that aim at 1) widening the base of the existing diverse community (academia and industry) by bringing in new actors traditionally not yet involved in the ACE/LSS research, and 2) preparing the ground for a stakeholder engagement strategy in the field of ACE/LSS as an input for establishing a long-term view of Life Support technologies to be developed in Europe. The related research outcomes are:

- the Position Paper - Consolidating the Swiss activities and rationale for ALSS and MELiSSA development (RO2.6.a, as well as RO2.3 and RO2.8.b)[486];
- the BELiSSIMA Phase A project (RO2.6.b, as well as RO2.4)[487] and more particularly its technical note TN.118.1.6[488];
- the proceedings of the ESA Closed Habitat Forum 2016 (RO2.6.c, as well as RO2.8.c and RO3.2), which short project description is presented hereafter in §10.1.

10.1 ESA Closed Habitats Forum (RO2.6.c, RO2.8.c, RO3.2)[489]

As mentioned above, the proceedings of the ESA Closed Habitat Forum 2016 is a component of the stakeholder engagement strategy for consolidating the current Swiss activities and rationale for LSS and MELiSSA development into an active and productive cluster (RO2.6.c).

The ESA Closed Habitat Forum 2016 is also an event participating to the promotion of education and communication activities related to ACE and LSS (RO2.8)[490] and its methodology is aimed at fostering ACE contribution to terrestrial sustainability (RO3.2)[491].

The section presents the objectives and methodology of the ESA Closed Habitat Forum 2016.

As a follow-up to the conclusions of the ESA Closed Habitats Forum, an ESA TAS project was defined order to do start establishing standards for closed habitats[492].

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[486] Cf Executive summary in §7.1; Annex B1.

[487] Cf short project description in §8.

[488] Cf Annex C2.

[489] ESA Closed Habitat Forum objectives, methodology and proceedings were prepared by UNIL and ESTEE in close collaboration with ESA-ESTEC and in particular with Brigitte Lamaze.

[490] Cf §12.

[491] Cf §14.

[492] Cf §13.4.

10.1.1 Short project description

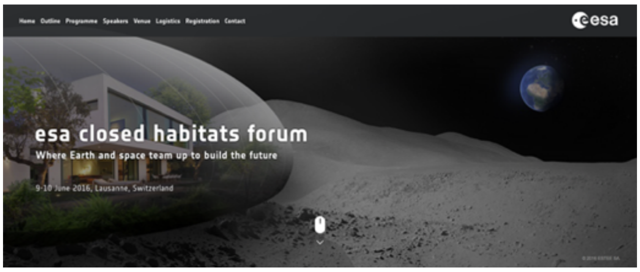
Project title: ESA Closed Habitats Forum

Client: ESA

Venue: UNIL

Organisers: UNIL, ESTEE

Date: 2016



In 2015, ESA published its Strategy for Space Exploration based on the 4 strategic goals endorsed at the Council meeting at Ministerial level in December 2014 through adoption of the resolution on the ESA Space Exploration Strategy and related to areas (science, economic growth, inspiration and global cooperation) in which space exploration could create concrete opportunities to deliver benefits for society. To create and capitalise on those opportunities, ESA has been taking a more proactive role in fostering synergies between space and terrestrial R&D activities, and initiated the 'ESA Open Innovation Exchange' project. The project intended to raise awareness on scientific and technical research of common space/non-space interest, better define ESA Technological Programs, and possibly investigate collaborative partnerships identified during vis-à-vis events between ESA and non-space industries. As an initial phase of a more articulated effort, ESA has been organising a series of Workshops/Forums addressing different scientific and technological fields, pertinent to both space and terrestrial applications. In particular, the Closed Habitats Forum has been targeting the synergies in the field of resources (mainly water, air, food, waste, energy) sustainable management and safety (i.e. safe use by humans).

More than 130 participants joined the first ESA Closed Habitats Forum in Lausanne, hosted at UNIL, and organised in close collaboration among ESA, UNIL and ESTEE. The forum attracted a comprehensive community from various disciplines, backgrounds, and countries and initiated a brainstorming about synergies between Earth and space regarding CH.

✧ *Forum objectives*

The purpose of the Closed Habitat Forum 2016 was to foster synergies between terrestrial and space exploration's sciences, R&D and technologies in the field of resource sustainable management and safety (i.e. safe use by humans)[493] in order to capitalise on investments in Life Support Systems and Space Exploration activities for civil markets/societal benefits (including emerging societal challenges) and leverage on terrestrial research for space exploration.

The ESA Closed Habitat Forum 2016 aimed at engaging terrestrial and space industrial communities to:

- Initiate a dialogue on scientific and technical research of common interest.
- Strengthen European collaboration and excellence in science and technology R&D.
- Incentivise non-space industry to engage in space activities and with ESA.
- Create a steady flow of collaborative partnerships (spin-ins and spin-offs).
- Foster creativity, innovation and new markets derived from the field of space exploration R&D.

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[493] Cf Annex E1.

- Foster the creation of a European community in this specialised field and build knowledge and momentum in Europe among this community for space exploration.
- Put a particular attention on potential contribution to essential technologies identified for emergency civil population situations.

The Forum featured 3 technical sessions[494] addressing key themes in the field of resource sustainable management and safety:

✧ *Sustainable resource management*

The splinter session focused on material and energy flows, with a closer look on how these flows can be looped and intertwined to achieve a more sustainable resource management. In space, extremely efficient closure of Life Support Systems is vital for long-term viability of the habitats. On Earth, more efficient recycling processes as well as more efficient use of resources are key challenges regarding sustainability. Water, air, food, and waste management were addressed, as well as the integration of eco-technologies into a fully functional CH for space or terrestrial environments. More specific discussion topics included re-use of wastewater in the context of precision and urban farming, atmospheric CO_2 valorisation into organic chemical compounds through biorefinery processes, as well as bioremediation and micropollution removal. Topics related to IE and circular and green economy, addressing resource valorisation, and material and energy flows at larger scale, were also discussed in this splinter session.

✧ *Sustainable habitat*

The splinter session focused on the habitat itself, the ‘shell’ hosting the above-mentioned processes. Modular, multifunctional, small and yet habitable space habitats are key components of space missions. More sustainable terrestrial habitats, in particular in dense urban environments, are also becoming essential challenges to be addressed regarding sustainability. Both construction and design of sustainable habitats will be addressed. More specific discussion topics included ecomaterials, advanced materials and bio-inspired architecture, as well as habitability, ergonomy, and autonomous habitat.

✧ *Smart monitoring and system control*

The splinter session was addressing the monitoring and regulation of the material and energy flows that circulate within a truly smart habitat. In space, monitoring the health of the crew and the system control of the LSS and of the CH in general is essential for providing a safe environment and thus ensuring the success of the mission. On Earth, smart monitoring technologies are very useful to offer a more personalised and better performed sensing of the environmental conditions of the habitat (such as indoor air quality and habitat surfaces microbiological quality) and inhabitants health status. It also allows to a more elegant use of resources and provides a better quality of life in a healthy habitat.

Keynote presentations introduced the different technical sessions and serve as a catalyst for the following splinter sessions discussions, during which participants will be asked to answer crucial questions, brainstorm and exchange ideas on the potential links between terrestrial and space activities.

Participants’ contributions were summarised in the final Forum proceedings and recommendations[495]. The following major topics were discussed, in terms of their state of the art and outlook, and the main

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[494] The forum methodology guidelines are provided in Annex E2b and the forum recommendation canvas used for the splinter sessions is available in Annex E2b.

[495] Cf Annex E3.

outcome from the brainstorming sessions were:

- Sustainable resource management:
    - Make sustainable resource management and recycling economically attractive;
    - A modular and generic test platform / demonstrator should be developed to test, experiment, promote, advertise, educate about, demonstrate engineering capabilities regarding sustainable resource management;
    - A new methodology to define and express basic/essential needs should be developed;
    - Give a push to policy changes towards being more a driving than a constrictive force;
    - Raising the level of awareness about sustainable resource management.
- Sustainable habitats:
    - The need to change the current mindset about the concept of habitat, from the segregating perception of the human on one side and habitat/machine on the other side;
    - Material management and building process to be revisited in a more sustainable approach;
    - The need to study how to make the volume of interior space more efficient.
- Smart monitoring and system control:
    - The need to develop a global design approach/methodology to improve the efficiency/usefulness of monitoring/control;
    - The need to develop new tools based on modelling and prediction;
    - Autonomous health management was highlighted as a key specific application in the field of smart monitoring and control.

As general conclusions of this event, the following needs were highlighted:

- A need of a reference leading entity federating and coordinating actions in various fields such as science and technology, education and dissemination, and leveraging constraints.
- A need to apply a systematic approach to achieve each milestone defined:
    - revisiting the definition of requirements, including new habitat concepts, global design approach and all other missing parts as of today; regarding the specific aspect of synergies between terrestrial and space applications, define earth/space specific part and context-free requirements;
    - identifying scenarios;
    - defining topics of investigation;
    - creating focused working groups.

11 Towards an ACE ground demonstrator in Western Switzerland (RO2.7)

In connection with the previously discussed elaboration of a stakeholder engagement strategy for consolidating the current Swiss activities and rationale for LSS and MELiSSA development into an active and productive cluster (RO2.6), Part IV of Oïkosmos Report 'Towards an ACE ground demonstrator in Western Switzerland?' (Figure 20)[496] aimed to demonstrate the opportunities offered by the hosting of an ACE ground demonstrator based in Western Switzerland for its innovation ecosystem and for the Swiss space sector (RO2.7).

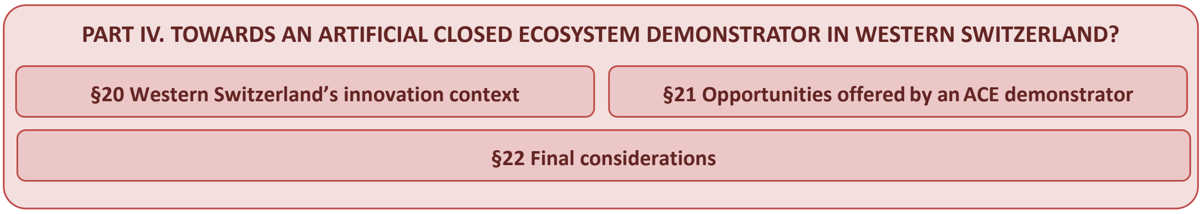

Figure 20: Part IV of Oïkosmos Report [497].

In general (Western) Switzerland offers substantial instruments for its economic promotion and the attraction for high-level initiatives thanks to[498]: its international and multilingual environment, its privileged relations with the European Union, its ideal central location for access to the European market, an exceptional quality of life and working environment, stable labour legislation, including one of the best intellectual property protection and excellent information security, authorities at the service of business with incentives and moderate corporate taxation, political stability, environmental security, reputable academic institutions, efficient services and state-of-the-art infrastructure.

(Western) Switzerland forms a veritable 'innovation ecosystem', which also provides key assets in order to favour the establishment of research synergies with the Oïkosmos programme and make the region attractive for one day hosting an ACE simulator[499], namely:

- a central geographical location in the heart of Europe;
- a dynamism thanks to a highly qualified and productive workforce. The "Swiss quality" label is based on work (productivity), products (precision and quality), multidisciplinary know-how, a motivated workforce and efficient infrastructures;
- its policies to support research and innovation promoted by its authorities;
- a scientific power thanks to an extremely dense ecosystem of players in the 'Research-Innovation-Market' value chain. (Western) Switzerland offers a range of actors, institutions and facilities relevant to the various stages of the Research-Innovation-Market value chain in particular: reputable academic research institutions, both at the level of basic and applied R&D[500]; the presence of university hospitals, such as the Centre hospitalier universitaire

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[496] Cf Annex A-§20-§22.

[497] Cf Annex A-Part IV.

[498] Cf Annex A-§20.1.

[499] Cf Annex A-§20.2.

[500] Cf Annex A-§5.2.1.

vaudois[501], the Hôpitaux de Genève and the Bern Inselspital[502] to cite just a few; cutting-edge academic research infrastructures and facilities (such as technology platforms dedicated to life sciences)[503]; the presence of scientific and technological clusters[504] and innovation support platforms[505].

The following sections of Oïkosmos Report (in French) are an integral of part of the research output from this PhD study.

The context of innovation in Western Switzerland[506]:

- General characteristics and key assets of Western Switzerland[507];
- Structures, organisations and players in the 'Research-Innovation-Market' value chain in Western Switzerland[508]:
    - Academic research institutions in Western Switzerland[509];
    - Technology platforms in Western Switzerland dedicated to life sciences[510];
    - Clusters in Western Switzerland[511];
    - Support for innovation in Western Switzerland[512];
    - Incubators and science and technology parks in Western Switzerland[513];
    - Private high-tech research centres[514].

The opportunities offered by an ACE simulator based in Western Switzerland[515]:

- Opportunities for the innovation ecosystem in Western Switzerland[516];
- Opportunities for the Swiss space sector[517]:
    - Swiss space policy[518];
    - Research institutions in the Swiss space sector[519];
    - Opportunities related to the implementation of the national space policy[520];
- Final considerations[521].

As a reminder, on the basis of its integrative approach, the Oïkosmos programme implies that

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[501] Cf Annex A-§5.2.1.2.
[502] Cf Annex A-§5.2.1.5.
[503] Cf Annex A-§5.2.1.7.
[504] Cf Annex A-§19.2.3.
[505] Cf Annex A-§19.2.4.
[506] Cf Annex A-§20.
[507] Cf Annex A-§20.1.
[508] Cf Annex A-§20.2.
[509] Cf Annex A-§20.2.1.
[510] Cf Annex A-§20.2.2.
[511] Cf Annex A-§20.2.3.
[512] Cf Annex A-§20.2.4.
[513] Cf Annex A-§20.2.5.
[514] Cf Annex A-§20.2.6.
[515] Cf Annex A-§21.
[516] Cf Annex A-§21.1.
[517] Cf Annex A-§21.2.
[518] Cf Annex A-§21.2.1.
[519] Cf Annex A-§21.2.2.
[520] Cf Annex A-§21.2.3.
[521] Cf Annex A-§22.

stakeholders from all disciplines can, as a matter of principle, interact strongly through a collective and cooperative strategy[522]. The aim is therefore to foster the participation and collaboration of communities of researchers from the various disciplines formulated in the research agenda[523]. However, it emerges from the report that many of them do not (yet) perceive today that they could be directly concerned by such a project. One of the challenges is therefore to encourage them to participate and to demonstrate to them the potential added value of integrating their skills, both from a space and terrestrial point of views, via research synergies. It should be noted that these stakeholders are not limited to academic research institutions alone, but include all the players in the Research-Innovation-Market value chain[524].

In summary, the fourth part of Annex A highlighted the advantages of Western Switzerland's participation in the development of an ACE demonstrator, which represents a way: to strengthen Swiss institutional participation in ESA activities - which seems all the more relevant since ESA sometimes has difficulties in financing space projects carried out in Switzerland; to bring together under a single umbrella a unique panel of strategic technologies for Switzerland, within a platform integrating interdisciplinarity upstream of its development, from the early R&D phases; to consolidate the existing dynamics between economic promotion, entrepreneurship and innovation; and to strengthen the region's position as a centre of excellence on the European eco-innovation map.

According to the Oïkosmos Report conclusions, it would therefore be desirable for Western Switzerland to develop an institutional strategy in favour of its participation in the Oïkosmos programme and to encourage the progressive setting up of an ACE simulator in the region. With the above-described assets and context[525], the interest should be clear on the ESA side.

In addition, the Position paper on ALSS[526] highlighted the ongoing and possible future collaborations from the emerging Swiss cluster on ALSS. In particular, it recommended to pursue the current momentum on space and terrestrial ALSS-related activities in Switzerland - especially within the MELiSSA framework - could notably aim at ground demonstration level[527] at:

- participating in the development of a MELiSSA-related state-of-the-art technological platform for eco-innovation;
- optimising the use of existing infrastructures and research facilities and services for showcasing and communicating societal benefits to the general public, decision makers and media.

The Position Paper also suggested to further consider developing a dedicated testbed in Switzerland to experiment ALSS concept in a short to mid-term perspective, as 42% of the organisations responding to the survey considered as “Access to advanced space R&D facility/hardware” as one of the most interesting MELiSSA asset (Q10) and close to 50% considered as expected outcome the “Participation in technology demonstration/showcase (technological component/module, prototype, emerging technology or applications, business incubator, etc.)” (45%) (Q18). Moreover, it notably came out of the survey that almost 80% of the responding organisations would be interested in having access to some MELiSSA laboratory/testbed hosted in Switzerland (Q20).

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[522] Cf §5.2.1.1.

[523] Cf Annex A-§7 to §10.

[524] Cf Annex A-Part III and Annex A-§20.2, Annex B1 and Annex C2.

[525] Cf Annex A-§20 and §21.

[526] Cf §7.

[527] Cf Annex B1-§2.1.3.3.

In addition to the attributes of its innovation ecosystem for business development, Switzerland should be envisaged as a very sweet spot for hosting an ACE ground demonstrator based on the analogy of the country itself with CH, as exemplified by:

- its geographical situation as a landlocked country;
- its difficult access to the mountain region;
- its limited dissipation of some organic pollutants from anthropogenic flows thanks to highly dense wastewater treatment plant network;
- its limited farming capacity compared to the surrounding countries.

This also means that ACE and CH spun-out technological solutions are directly relevant for Switzerland itself.

Finally, as highlighted in §13.2, the main goal of ESTEE SA is to build a proof of concept of CH in Switzerland, namely the Scorpius Prototype 1 (SP1), for the on-ground demonstration of ACE integrating main ALSS functions with TRL 2/3 to 5/6.

12 Institutional dynamics, education and communication activities (RO2.8)

With the objective to foster the institutional dynamics for ACE and LSS development in Switzerland and promote related education and communication activities (RO2.8), this work initiates the following activities:

- Proposition of accompanying measures, recommendations and suggestions to the Direction of the University of Lausanne (RO2.8.a)[528];
- Elaboration of the Position Paper - Consolidating the Swiss activities and rationale for ALSS and MELiSSA development (RO2.8.b, as well as RO2.3 and RO2.6.a)[529];
- Organisation of ESA Closed Habitat Forum 2016 (RO2.8.c, as well as RO2.6.c and RO3.2)[530] and MELiSSA Workshop 2016 (RO2.8.c)[531];
- Lecture, teaching and co-organisation of EPFL ENAC 'Building on Mars' teaching unit (since 2012) (RO2.8.d)[532];
- Participation in conferences and seminars as a speaker for various academic, public and specialist audience (RO2.8.e)[533];
- As well as two main mentorship activities[534]:
    - ESA_Lab IGLUNA pilot project I (2018-2019) – Mentorship for an interuniversity demonstrator project[535];
    - Mission Asclepios 2020-2021 – Mentorship for project proposal for a student space mission analogue made for educational purposes based at EPFL[536].

Figure 21 positions the respective RO2.8-related activities along the terrestrial and space dimensions of LSS research domains, as well as specifies the kind of roles the present author was involved in.

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[528] Cf §12.1; Annex A-§23 and §24 .

[529] Cf Executive summary in §7.1; Annex B1.

[530] Cf short project description in §10.1.

[531] Cf Oïkosmos talk in Annex F1b.

[532] Cf pedagogical concept in §12.3; and article published in Proceedings of the International Conference Structures and Architecture 2013 in Annex F2b.

[533] The list of the talks is given in Annex K, e.g. MELiSSA 25th anniversary 2014, New Worlds conference 2017, European Mars Convention 2018 (EMC18) and MELiSSA conference 2020.

[534] Cf §12.3.

[535] Cf Annex F3.

[536] Cf Annex F4.

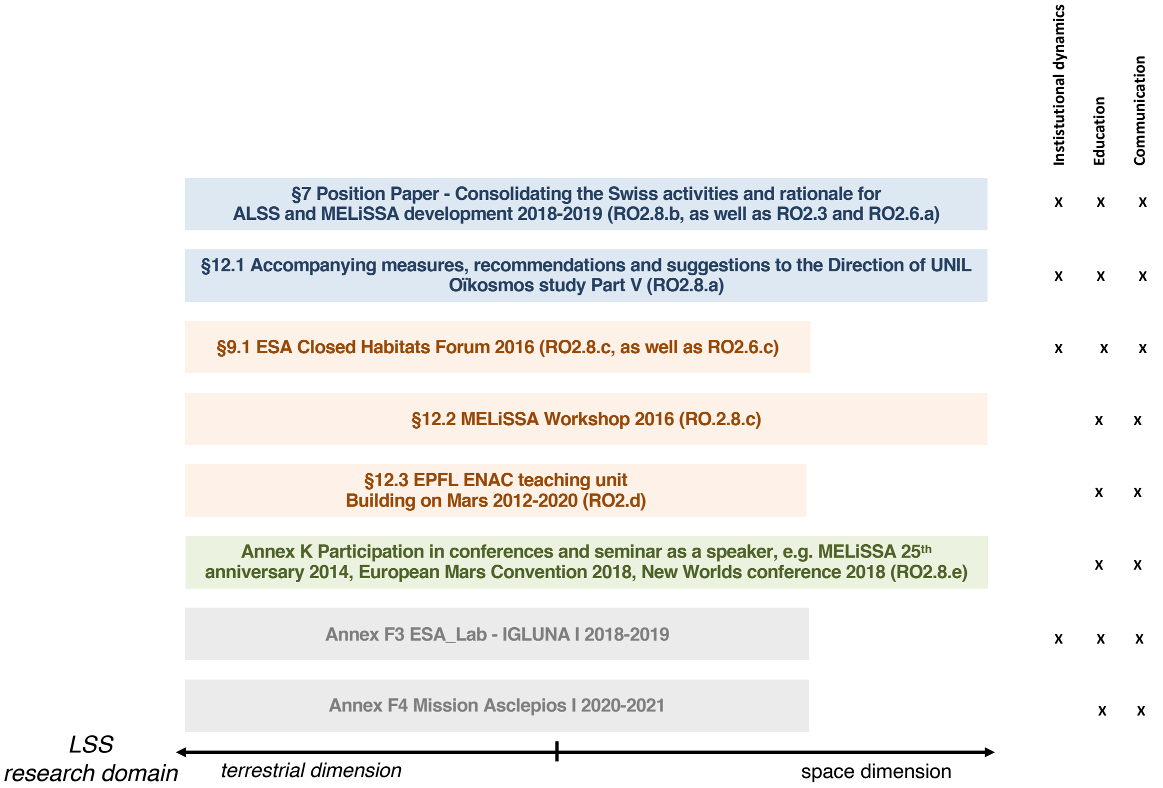

Figure 21: Positioning of RO2.8-related activities.

Positioning of the respective RO2.8-related activities to foster institutional dynamics for ACE and LSS development in Switzerland and promote them through education and communication, along the dimension of the LSS reseach domain.

Reference to other RO is mentioned, as well cross-reference to other chapters.

All the activities were deployed in the framework of this thesis at UNIL and/or of the development of Earth Space Technical Ecosystem Enterprises SA (ESTEE, see RO3.1). The activities mainly involved the following roles: authorship (in blue); organisation, coordination and lecture (in orange); lecture only (in green); and mentorship (in gray).

12.1 Accompanying measures, recommendations and suggestions to the Directions of UNIL in Oïkosmos Report (RO2.8.a)

The final part of Oïkosmos Report (Figure 22) notably provides:

- accompanying measures[537] that would contribute to the dissemination of the Oïkosmos programme such as:
    - the elaboration of an appropriate science policy[538];
    - the adequate planning of its communication[539];
    - the exploiting its potential for science education[540].
- recommendations and suggestions to the Direction of the University of Lausanne[541].
- final conclusions[542].

PART V. ACCOMPANYING MEASURES, RECOMMENDATIONS AND CONCLUSIONS

§23 Accompagnying measures (science policy and communication, pedagogical aspects)

§24 Recommendations and suggestions to the Direction of UNIL

§25 Final conclusions

Figure 22: Part V of Oïkosmos Report [543].

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[537] Cf Annex A-§23.
[538] Cf Annex A-§23.1.
[539] Cf Annex A-§23.2.
[540] Cf Annex A-§23.3.
[541] Cf Annex A-§24.
[542] Cf Annex A-§25.
[543] Cf Annex A-Part V.

12.2 MELiSSA scientific Workshop

Project title: MELiSSA scientific Workshop

Client: ESA

Venue: UNIL

Organisers: ESTEE, UNIL

Date: 2016

ESTEE and UNIL co-organised the 2016 MELiSSA Scientific Workshop, with more than 150 attendees. The objective of the workshop was to provide a platform for presenting MELiSSA challenges and results, and to prepare for future research topics and collaborations. The workshop comprised the following successive thematic sessions:

- Session 1- Waste processing;
- Session 2 - Water recycling;
- Session 3 - Air recycling;
- Session 4 - Food production & preparation;
- Session 5 - Chemical & microbial safety;
- Session 6 - System tools.

The book of abstracts is annexed[544], as well as the slides of Oïkosmos presentation[545].

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[544] Cf Annex F1a.

[545] Cf Annex F1b.

12.3 Pedagogical concept of EPFL ENAC ‘Building on Mars’ teaching unit (RO2.8.d)

Developmental phase for an extraterrestrial habitat implies a space architecture that ‘graduates to treat the same range of needs and issues that characterize terrestrial architecture (…): complete accommodations for all stages, aspects, activities, and needs of human living’ (Sherwood 2017), e.g. in terms of urban development, habitation, food sourcing, waste processing, maintenance, recreation, etc. This approach offers interesting training perspective.

As mentioned in Annex A-§23.3, the ENAC Teaching Unit (Unité d’enseignement ENAC, UEE) ‘Habiter Mars’ conducted at EPFL since 2012 is a concrete example of an approach related to CH aiming at offering an educational and interdisciplinary added value to students. This semester-long project brings together one afternoon a week final-year Bachelor students from the three sections of the ENAC Faculty (architecture, civil engineering and rural engineering). The teaching of the UEE Habiter Mars, in which the Industrial Ecology group has been strongly involved, is organised around a practical task which consists of developing a proposal for a Martian base in a group. This is done in two phases (see Annex F2a for a full description of the course). The first phase aims to analyse the Martian context. Groups of students work out strategies for implementation (implementation site: geographical position, surface or underground), material (which material resources offer which constructive possibilities), structural (relationship between space, structure, materials), envelope (opaque, transparent, materials), supply of oxygen, water and food (vital needs/life support), production and storage and transformation of energy, and spatial organisation for various human activities. The participants in each of these groups thus become 'specialists' in a given theme (vital needs/life support, structure and envelope, building system, energy management, living on Mars, etc.). In a second phase, new teams are formed with a specialist from the groups of the previous stage. The aim is to bring together and adapt the various strategies that have been developed into a coherent project for a Mars station. On the one hand, this requires the study of constructive systems that are able to ensure the required performances such as structural safety, thermal insulation, air renewal, natural light, etc. to ensure the safety and climatic conditions required inside the base. On the other hand, the various elements required to create a closed ecosystem capable of providing a viable ‘Biosphere’ and to set up a sufficiently comfortable living environment for the colonists are determined and organised at both the functional and spatial levels (see Annex F2b for examples of student deliverables on LSS). Each group is supervised ‘at the table’ to check the technical feasibility of the proposals each week. This practical exercise is, of course, supplemented by theoretical lectures, presentations and seminars throughout the semester. During the first editions of this UEE, followed in total by nearly two hundred students, the problem of habitats subjected to the strong constraints of the Martian environment was fully integrated into the students’ training, allowing them to learn about the complexity of a project approach that must incorporate a multitude of sometimes contradictory aspects. For most of them, the exercise was their first practical experience of interdisciplinarity, as well as their first real collaboration with their colleagues from other ENAC Faculty training courses. In this context, the skills of each student were directly useful to the others, which allowed their effective integration in a common project.

The above pedagogical approach was the subject of a published article in the proceedings of the International Conference Structures and Architecture 2013 (Nussbaumer et al. 2013)[546].

The editions 2019 and 2020 of the UEE were connected to the first ESA_Lab campaign IGLUNA[547], an interuniversity demonstrator project for a lunar habitat. The objective of the IGLUNA project, coordinated by the Swiss Space Center, was to foster exchange among European students through participation in

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[546] Cf Annex F2c.

[547] Cf Annex F3.

an international, interdisciplinary, and collaborative platform of demonstration of life support systems in extreme environment (see Annex F3 for project brochure and modules list). Through its participation in the project, ESTEE provided its expertise and guidance in ALSS related technologies, including an automated greenhouse for plant production, which was showcased in a field campaign in Zermatt in summer 2019 inside the Glacier Palace at Klein Matterhorn and in an exhibition hall downtown in the village.

Another recent pedagogical activity started launched and coordinated by the EPFL student association Space@yourService is the Mission Asclepios 2020-2021[548] a student space mission analogue made for educational purposes which benefited from mentorship from ESTEE during project preparation.

In the specific context of ACE, initiatives such as UEE, IGLUNA and Asclepios are attracting education activities because they make student eyes sparkle and gives the opportunities to implement a project in unusual context in a 'think out of the box' mindset.

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[548] Cf Annex F4.

As a conclusion for Part II, Figure 23 contextualises the scope of research question 2 (RQ2) ‘How to cross-fertilise the terrestrial and space dimensions of LSS development?’ along the research axes of IE and LSS.

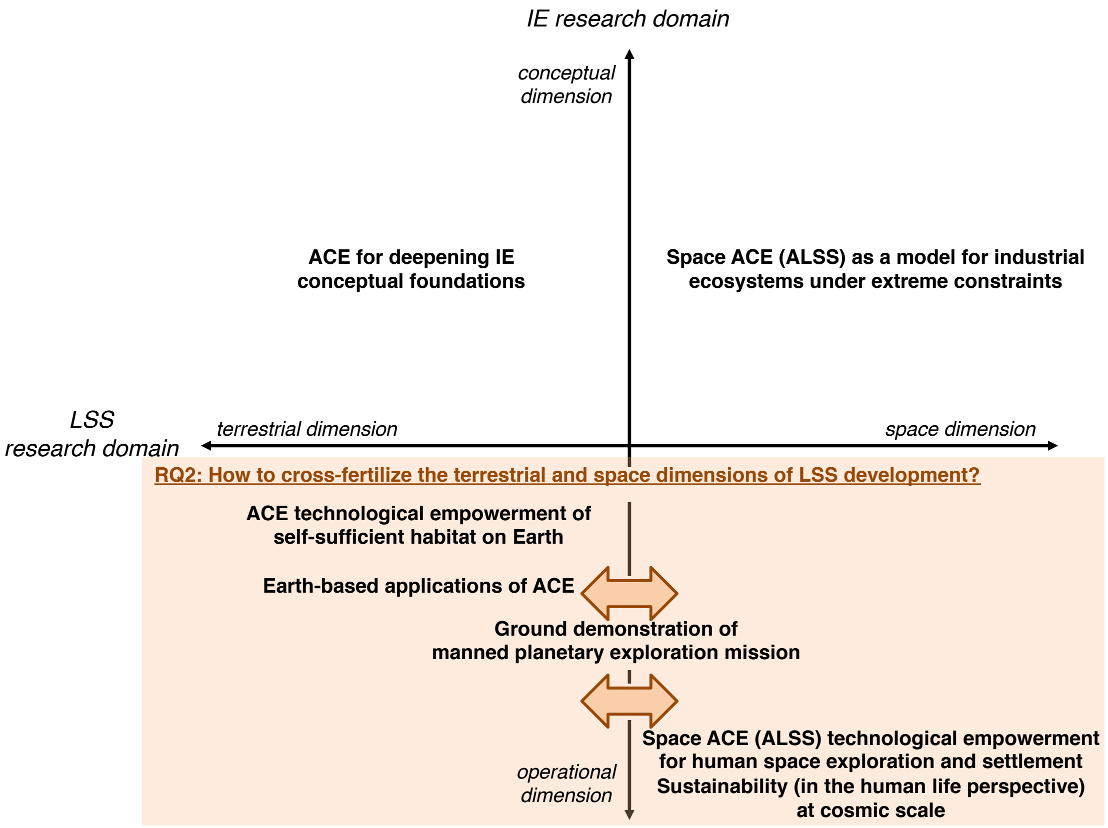

Figure 23: Scope of the research question RQ2 along the research axes of IE and LSS.
The second part of this work focused on the possible ways to cross-fertilise the terrestrial and space dimensions of LSS development. It covered the conceptualisation of R&D synergies, the exploitation of an ACE ground demonstrator, and the implementation of spin-in and spin-out R&D and prototyping projects, and continued with the engagement of stakeholders, the opportunity for Western Switzerland to host an ACE demonstrator, the promotion of institutional dynamics and education and communication activities.

The activities described in Part II showed how an ACE ground demonstrator can be instrumental for LSS development by providing synergies at the interface of its terrestrial and space dimensions.

PART III: CONTRIBUTIONS OF ARTIFICIAL CLOSED ECOSYSTEMS DEVELOPMENT TO THE OPERATIONALISATION OF INDUSTRIAL ECOLOGY (RQ3)

The third part of this PhD work tackles the contributions of ACE development to the operationalisation of IE.

Chapter 13 analyses the potential of ACE development for the technological empowerment of self-sufficient habitat on Earth (RO3.1). It introduces the context in which Earth Space Technical Ecosystem Enterprises SA (ESTEE) was created, as a continuation of the Oïkosmos Report (§13.1). Next, it describes the high-level specifications of two key projects of ESTEE, namely Scorpius Prototype 1 and Scorpius Laboratory Prototype 1 (§13.2), that aim at establishing a proof of concept of a CH and ACE demonstrator. Furthermore, it addresses the question of the habitability optimisation of CH, by exploring the notion of human habitat and the enhancement of comfort through user-building symbiosis (§13.3). Afterwards, it conceptualises CH as minimal habitats for self-sufficiency in the perspective of IE (§13.4). Finally, it provides considerations on the technology empowerment from ACE development for self-sufficient habitat on Earth (§13.5).

Chapter 14 compiles the contributions of ACE development to terrestrial sustainability (RO3.2), which flow from the ground preparation of manned planetary exploration missions and parallel development of specific ACE-based terrestrial solutions. It first summarises the contributions to terrestrial sustainability identified previously (§14.1). Next, it analyses the potential of ACE development for Earth-based applications (§14.2), by mapping their related possible market segments based on the Oïkosmos Report and on market research and stakeholders analysis (§14.2.1) and by describing an assessment of space ALSS technologies business and financial potential for Earth-based applications (EXPRO+ study, in which ESTEE led the technical side of the assessment, §14.2.2). Later, Chapter 14 introduces the notion of circular economy (§14.3) and presents a selection of contributions of ACE development to circular economy (§14.4). Eventually, it provides considerations on the contributions of ACE development to terrestrial sustainability (§14.5).

With the benefit of hindsight from the overall outcome of this research, Chapter 15 considers the possible ways to envisage sustainability (in the human life perspective) at cosmic scale (RO3.3). It introduces the emerging field of New Space (§15.1). It then discusses the rise of space tourism (§15.2) and examines space colonisation as a necessary expansion of humanity in the solar system (§15.3). Subsequently, it describes the approach of space sustainability (§15.4) and investigates the extension of the notion of space sustainability to cosmic scale (§15.5). Finally it considers the contributions of ACE development to space sustainability (§15.6).

13 Analysis of the potential of ACE development for the technological empowerment of self-sufficient habitat on Earth (RO3.1)[549]

In order to analyse the potential of ACE development for the technological empowerment of self-sufficient habitat on Earth (RO3.1), this monograph: it introduces the context in which Earth Space Technical Ecosystem Enterprises SA (ESTEE) was created, as a continuation of the Oïkosmos Report (§13.1); 2) describes the high-level specifications of two key projects of ESTEE, namely Scorpius Prototype 1 (§13.2.1) and Scorpius Laboratory Prototype 1 (§13.2.3), that aims at establishing a proof of concept of a CH and ACE demonstrator; 3) addresses the question of the habitability optimisation of CH, by exploring the notion of human habitat and the enhancement of comfort through user-building symbiosis (§13.3); 4) conceptualises CH as minimal habitat for self-sufficiency in the perspective of IE (§13.4); and 5) provides final considerations on the technology empowerment from ACE development for self-sufficient habitat on Earth (§13.5).

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[549] Related research outputs:

Self-sufficient habitats are discussed in the following sections of the associated research outputs of this study:

- Annex A-§10 on the possible characteristics of a CH, as an eco-, self-sufficient, autonomous, healthy and smart habitat;
- BELiSSIMA Phase A TN118.1.4 (Annex C2a-§7.5);
- ESA Closed Habitat Forum proceedings (§10.1 and Annex E3);
- Mapping of Earth-based applications of ACE (§14.2).

13.1 Introducing Earth Space Technical Ecosystem Entreprises SA

As highlighted earlier[550], the need for ground demonstrators is proven (e.g. in Antarctica, MELiSSA Pilot Plant, BIOS, Lunar Palace, etc.)[551]. Most space agencies develop a long-term roadmap for ground simulation of high TRL space LSS with humans. Still, few CH on-ground demonstration combining ALSS and humans are available nowadays. The part IV of Oïkosmos Report [552] demonstrated the opportunities offered by the hosting of an ACE ground demonstrator based in Western Switzerland for its innovation ecosystem and for the Swiss space sector (RO2.7).

Incorporated in 2013 in Lausanne, Earth Space Technical Ecosystem Entreprises SA[553] (ESTEE) precisely aims at establishing proof of concepts of such CH through a complete ACE demonstrator, namely the Scorpius Prototype 1 (SP1), integrating state-of-the-art ACE compatible technologies, and Scorpius Laboratory Prototype 1 (SLP1), a smaller and simplified version of the latter. SP1 and SLP1 are introduced respectively in §13.2 and §13.2.3.

With its connection to Oïkosmos programme (conceptualisation of the research on ACE), the present author being the first company employee and Managing Director, ESTEE could be considered to a certain extent as a spin-off side activity from the MELiSSA project to enable the operationalisation of the R&D on ACE in the form of a demonstrator, as well as specific Earth-based applications.

Founded and fully financed since the beginning by Omar A. Fayed, a private investor based in the UK, the vision of ESTEE is to facilitate both sustainable living on Earth and human space exploration through the development of technologies related to advanced LSS (Figure 24). ESTEE mission is to develop products that are designed and engineered to transform wastes into resources using bio-inspired and synergistic solutions. Towards this ambitious objective, ESTEE is developing systems that combine cleantechs, biotechnologies and physical systems operating in closed loops.

The combination in a (semi-)closed system is a bridging step towards the pioneering LSS development to make it possible to settle a permanent habitat on Mars. The terrestrial spin-off markets of ESTEE include small-scale solutions and devices that would increase the closedness of habitats, from organic waste valorisation to in-home food production. The expected outcome of these activities is to provide economically viable bioregenerative approaches improving sustainability on Earth, as well as facilitating long-term space travel and settlement. Prototyping, testing and operations are conducted in a facility located in Bussigny, with the company headquarters located in downtown Lausanne.

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[550] Cf §4.2.1 and §6.1.1.

[551] For a review of ALSS research in Soviet Union/Russia, United States, Europe, Japan and China which can support humans living in space, see Liu et al. (2021).

[552] Cf Annex A-§20-§22.

[553] Company website: https://est2e.com

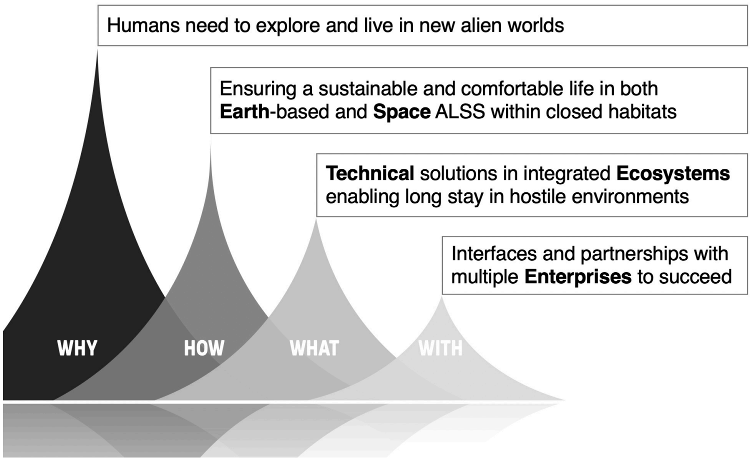

Figure 24: ESTEE vision.

In a nutshell, ESTEE aims at accelerating the technological transfer from space solutions to terrestrial ones, and vice versa. In this perspective, ESTEE's approach is to combine existing and emerging technologies that are engineered to transform wastes into resources using bio-inspired solutions. Therefore, ESTEE is positioned at the interface of space and terrestrial ALSS R&D, in order to ultimately facilitate and enhance the human capacity to settle a permanent habitat on Mars and in parallel the diffusion of eco-efficient Earth-based applications, e.g. for food production and wastewater treatment.

Towards its vision, ESTEE's strategy is to play both complementary and parallel roles of: integrator, by scaling and interfacing existing and emerging space and terrestrial technologies; investor, funding the technological development of CH; facilitator, fostering the building of an R&D and tech transfer ALSS community; and industrial partner, prototyping, industrialising and commercialising ALSS-related solutions.

The assets of ESTEE are its structure as a private company and independent partner investing on building bioregenerative LSS and CH know-how; its fast prototyping means; its market orientations; its focus on user experience; its network access; and its role as a facilitator for technology integration.

13.2 Scorpius Prototype 1 (SP1)[554]

One of the core activities of ESTEE is the design and construction of SP1, a (semi-)closed prototype integrating existing and emerging ALSS technologies. The prototype was designed in-house in 2017-2019 by ESTEE's engineering team. As a self-sufficient terrestrial habitat prototype, SP1's approach is to integrate proven and emerging ALSS-related technologies. It aims to become a proof-of-concept of a fully integrated ALSS, a platform for technology assessment and a ground demonstrator of a high level of material loop closure within a sustainable habitat. SP1 objective is to leverage know-how from terrestrial research to space LSS development (spin-in), and also to enhance the development of Earth-based application from space ALSS (spin-out).

The main high-level design specifications of SP1 are as follows:

- design for 2 crew members for long-duration missions on ground (up to one year of autonomy);
- loop closure as high as possible with very high target water recycling within the prototype (>95%) and recycled waste within the prototype (>90%);
- no soil for plant cultivation and no access to natural light
- artificial lighting-based plant cultivation (as only indoor operations are considered);
- composed of continuous atmosphere within the prototype (habitat module and technical areas);
- composed of less than 1 cubic metre of consumables for the entire mission;
- once started, its mission will not allow any material import or export after closure
- limited budget (time and money), all covered by company own funds;
- modularity (ship container size), to be transported by truck;
- planetary base design orientation/inspiration;
- based on a high degree of automation and monitoring for easiness of operation, safety, and minimal maintenance carried out by users;
- modules TRL range from 2 to 5(6), depending on the technological system dimension.

The following parameters are not taken into consideration as a design criteria or constraints: weight; energy consumption; radiation protection; outdoor conditions (such as extremely low or high temperature).

Figure 25 shows an artist view of SP1 in a Martian context.

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[554] This section gives an overview of the design specifications of two of its core projects, the Scorpius Prototype 1 (SP1) and Scorpius Laboratory Prototype 1 (SLP1).

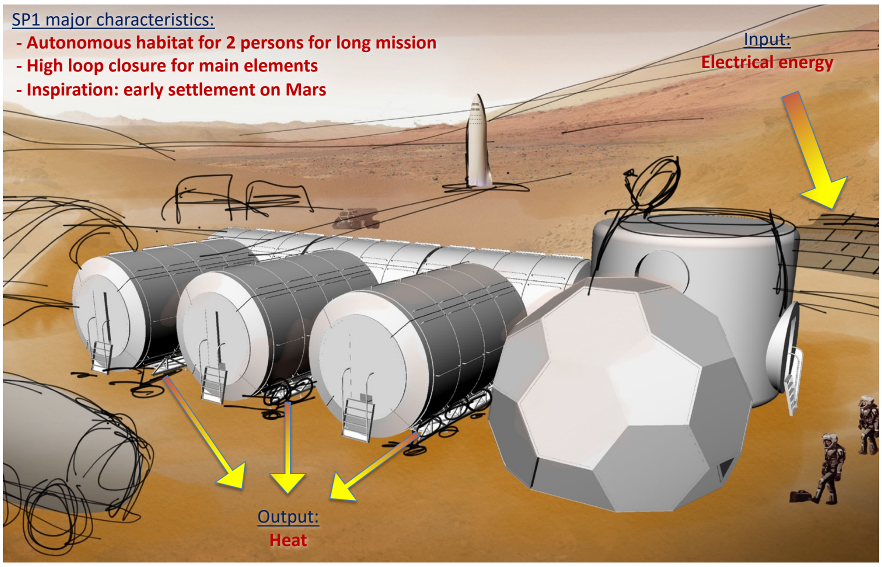


Figure 25: Artist view of SP1.
SP1 targets a high loop closure for main elements and has been designed in order to: become a proof of concept of a CH demonstrator, integrate state-of-the-art ALSS compatible technologies and enhance the preparation and financing on Earth of manned space missions. One design criteria for Mars compatibility is the shape of the habitat to handle the pressure difference mean atmospheric pressure on Mars of 600 Pa compared to 101'325 Pa for the atmospheric pressure at sea level on Earth. In consequence, cylindric and semi-spherical structure are preferred. Otherwise, the prototype for to terrestrial conditions. Credits: ESTEE, 2018

The prototyping fields for the SP1 development roadmap are given in Figure 26.

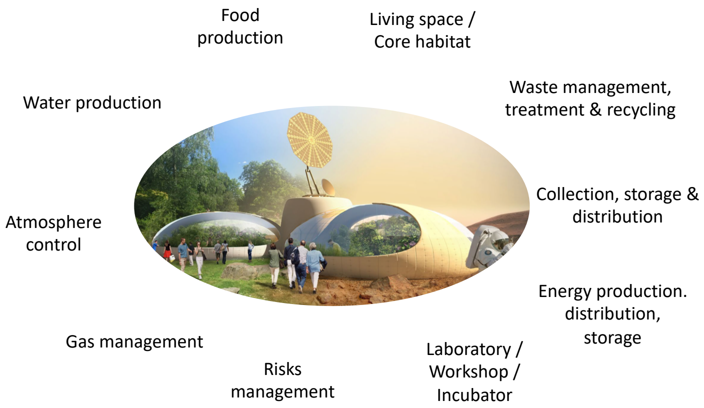


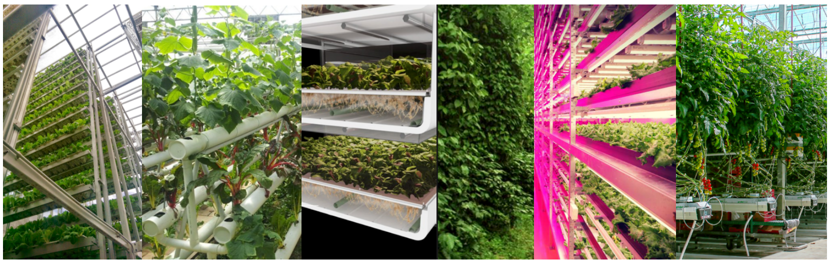
Figure 26: SP1 prototyping fields.
The SP1 project is divided into different prototyping fields: food production; waste management; water production; living space / core habitat; collection, storage and distribution; atmosphere control; gas management unit; energy production; laboratory / workshop / incubator; habitable garden; crew; system management.
The initial design of SP1 notably proposes the following technical functions: greenhouse for aeroponic food production (vertical fogponics for minimal water consumption); water management processes such as urine nitrification, nutrient recovery, water distillation and mineralisation, micropollutant removal, grey water treatment, atmospheric water condensation; energy supply from solar energy; tailored solution for comfort and habitability. Source: ESTEE, 2017.

SP1 is designed to perform the following typical life-support functions:

- Air revitalisation: CO_2 uptake, O_2 regeneration, temperature and humidity control, air contaminant (including odor) control;

- Water recovery and recycling: collection, treatment/purification, and disinfection of grey water, water from the oxidation of organic waste, urine nitrification, nutrient recovery, micropollutant removal;
- Food production and preparation: diversified food production in aeroponic-based greenhouses, food transformation and storage;
- Waste transformation and nutrient recovery: collection and storage of organic wastes, including inedible plant waste and metabolic wastes (faeces and urine); and oxidation of the waste by a combination of physicochemical and biological processes;
- Accurate and automated control and command;
- Shelter promoting a sense of comfort, curiosity, and personal development.

For each function a technology assessment has been pursued. Figure 27 shows an example of a short summary for hydroponics systems assessment (e.g. aeroponics and fogponics).



Credits: Aerofarms, SkyGreen, Philips

Advantages

- Possibility to finely regulate the environmental conditions
- Low water consumption
- Compatible with zero-gravity environment
- Extremely compact
- Highly productive
- Can be very simple and highly modular layout
- Low energy consumption (except if using only artificial lighting)
- ESTEE experience

Limitations

- Nutrient solution composition might need to be adjusted for each crop during growth cycle
- Rather expensive (notably lighting systems)

Figure 27: Technology assessment summary for hydroponics systems.

An overview of SP1 is shown in Figure 28, with the living space, three greenhouses and three different modules, and a habitat garden.

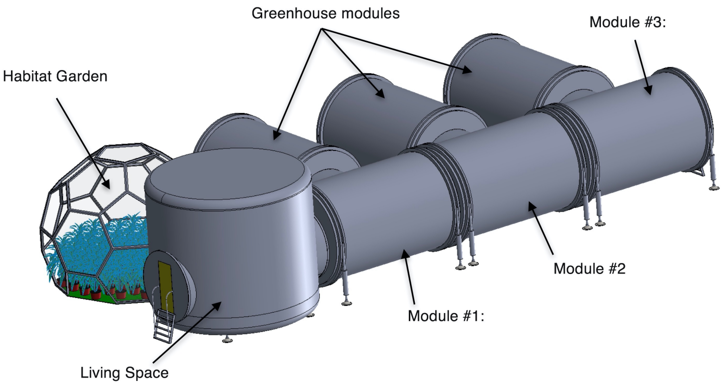


Figure 28: Overview of SP1.
The dimensions of each module (living space excluded) are of a diameter 4.14 m and a length of 6 m. Those dimensions are chosen to be transportable using road transportation.

Figure 29 shows SP1 overview within ESTEE facility showroom.

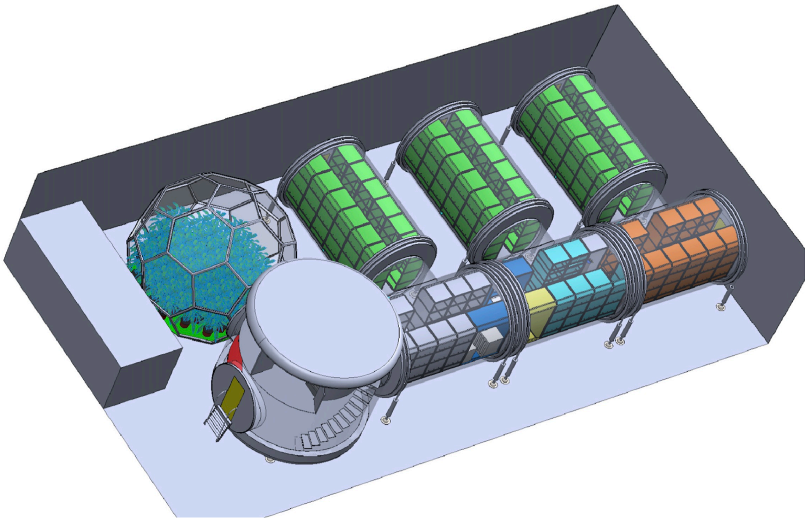


Figure 29: SP1 overview within ESTEE facility showroom.
Source: ESTEE, 2018.

An inside view of the module 3 is shown in Figure 30.

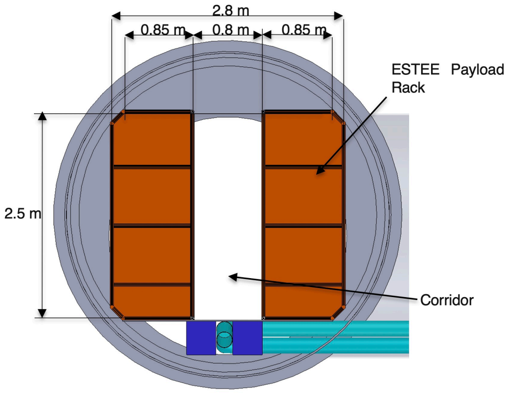


Figure 30: Radial cut of module 3.
On the left and right side of the corridor are fixed the payload rack. This standard cabinet is designed to fit perfectly the SP1 modules. It is 2.5 m high, 1 m width and 1 m deep. All technical matter is fitted inside and a front sliding door will allow an ease of access to its content. The passage through the tube is defined by a rectangle of 2.5 m high and 0.8 m width. The space between the racks and the tube structure is used to pass pipes, electrical wires and components, etc.

A simplified scheme of SP1 functional modules is shown in Figure 31.

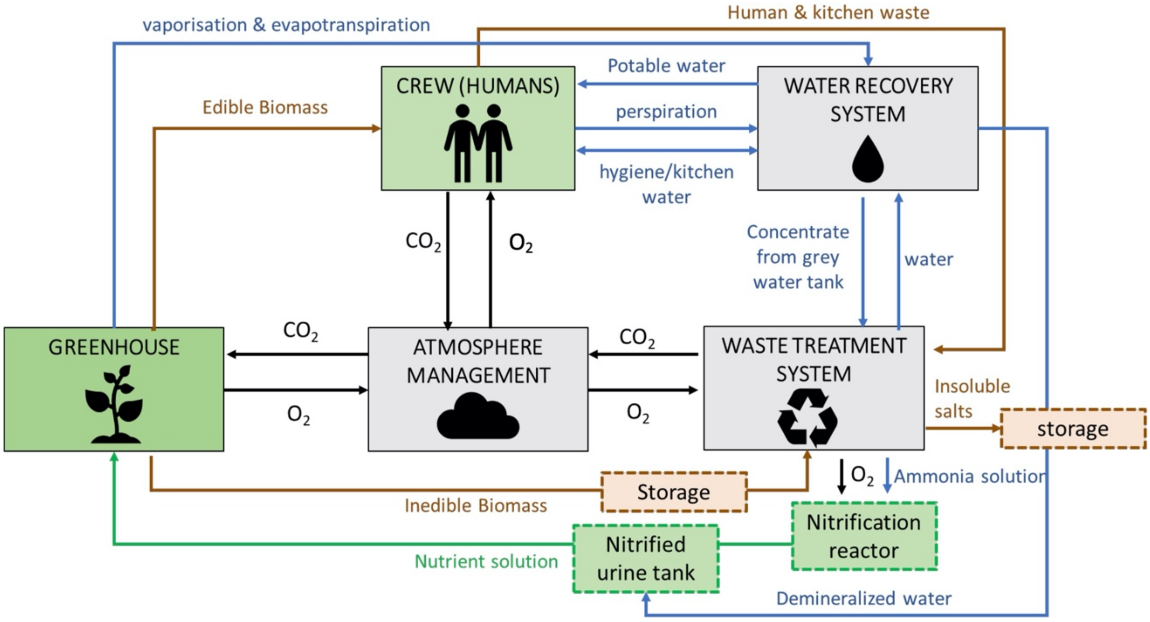


Figure 31: Simplified scheme of SP1 functional modules.
As an ACE demonstrator, SP1 is composed of modular technological units and based on bioprocesses such as urine nitrification, growth chamber for higher plants production, and supplemented by physicochemical subsystems for wastewater treatment, as well as mineralisation process, All modules operate together in a closed-loop fashion to ensure the highest possible rate of material recycling.
Biological subsystems are highlighted in green, whereas subsystems based on physicochemical processes are shown in grey. Hygiene water stands for bathroom and laundry wastewater. Source: ESTEE, 2018.

The concept, the design, the materials and the systems selected for the construction of the structure and the envelope of the ACE demonstrator will have to comply to any applicable regulation in the country of installation of the demonstrator. For instance, the structural design and performance will be based and assessed according to established design standards, such as the Swiss SIA 260 (Basis for the elaboration of the projects of supporting structures) and SIA 261 (Actions on supporting structures). In addition to the structural aspect, the envelope of the ACE demonstrator must fulfil a level of air tightness that has to be representative of a CH, while keeping the system relatively simple and affordable; sufficient heat insulation and moisture barrier; proper sound insulation and vibration propagations prevention to the adjacent LSS modules; and a good level of visual finish, with smooth and even painted or treated surface.

An ACE demonstrator such as SP1 has to fulfil user needs by offering its crew:

- clean breathable air, with balanced O_2, CO_2 and N_2 composition; amount of pollutants (e.g. COVs, fine particles, etc.) and with microbial levels at least below the highest safety standards;
- clean water, with low amount of organic compounds (e.g. bioactive molecules such as drugs or hormones residues, plastic residues, hydrocarbons, endocrine disruptors, etc.) and inorganic (heavy metals, etc) pollutants, low amount of microbes in tanks; sterile water at tap, etc.;
- balanced and tasty diet, with appropriate amount of glucides, lipides, proteins, minerals, vitamins, etc., diversity of crops and varied recipes for meals plan;
- comfort, with appropriate air conditions (in terms of temperature and pressure; etc.), lighting (light intensity, spectrum, quality and distribution (space, time), noise level;
- design, in terms of user-friendliness, operability (automation level), aesthetics;
- psychology, in terms of intimacy, internal and external human interaction/communication;

- safety, in terms of operational safety (modularity, back-up), accident prevention (fire, explosion, etc.), biosafety (incl. food safety), protection from external threats (incl. cybersecurity)
- and transversal needs such as:
    - self-sufficiency: recycled fraction of a resource;
    - tolerance, e.g. the user can wait if need-fulfilling is disrupted: air: few minutes for oxygen, few weeks for pollution; water: few hours for microbes, few weeks for pollution; diet : few hours for glucides, few weeks for some micronutrients;
    - latency, e.g. time between system set-up and need fulfilment.

As for humans, the organisms needs have obviously to be satisfied, with optimal air composition for photosynthesis and optimal nutrient delivery solutions for the crop growth, to cite just the example of plant production.

Some variables (self-sufficiency, tolerance, latency) can be analysed exclusively at system-level, and not subsystem level, such as food, air, water, etc.

Requirement levels, based on the level of closure, can be attributed for each need, as exemplified in Table 9.

Air	0	1	2	3	4
Quantity	No air supply required	25% volume	50% volume	75% volume	100 % of air needed has to be provided by the system
Quality	No air quality requirement	Air has to be free of any gas/microbial pollutant known as presenting a short-term threat on survival.	-	Air has to be free of any gas/microbial pollutant known as causing some discomfort or long-term health hazard to the users.	Air has to be free of any gas/microbial pollutant known as presenting any health hazard.
Self-sufficiency	The system does not have to operate off-grid.	The system should operate continuously without any material or energy input for at least one day.	The system should operate continuously without any material or energy input for at least one week.	The system should operate continuously without any material or energy input for at least one month.	The system should operate continuously without any material or energy input.
Tolerance	Not an issue if needs are no longer provided.	Dirsuption of need satisfaction should not exceed few days.	Disruption of need satisfaction should not exceed few hours.	Disruption of need satisfaction should not exceed few minutes.	Needs must be satisfied continuously.
Latency	Needs can be satisfied anytime after setup	Needs have to be satisfied no longer than few days after setup.	Needs have to be satisfied no longer than few hours after setup.	Needs have to be satisfied no longer than few minutes after setup.	Needs must be satisfied immediately after setup.

Table 9: Example of requirement levels for air depending on the ACE closure level.
Requirement levels from 1 to 4 corresponds to an ACE closure level from 0% to 100%.

ACE implies to do more with less. To guarantee maximal levels of efficiency and utility, SP1 equipment must be multipurpose.

The following functional modules of SP1 are briefly described in §13.2.1: food production (§13.2.1.1), waste management (§13.2.1.2), water production (§13.2.1.3), core habitat (§13.2.1.4), habitable garden (§13.2.1.5) and system management (§13.2.1.6).

Afterward, the roadmap of SP1 is presented in §13.2.2.

13.2.1 SP1 functional modules

13.2.1.1 Food production

The food production function of SP1 regroups three tubular greenhouses (GH, plant cultivation area: GH^1-24 m^2, GH^2-36 m^2, GH^3-30 m^2), one which is shown in Figure 32, which aims to adapt, integrate and demonstrate plant cultivation and operations for safe food production.

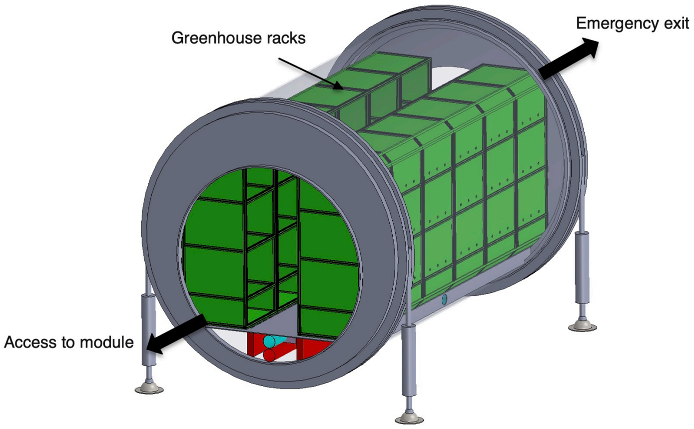


Figure 32. SP1 greenhouse module.
An emergency exit is placed in one of the extremities. A nutrients delivery system (NDS) is included in each module. The standard payload rack will be used to fix the plant racks, the illumination lighting system and the NDS. Source: ESTEE, 2018.

The greenhouse modules are equipped with two hydroponics systems: high-pressure aeroponics (HPA) and nutrient film technique. Figure 33 shows the high-pressure aeroponic system (HPA) prototype developed at ESTEE to be used for SP1. Certain nutrient content, pH, EC level, nutrient solution volume are monitored and controlled by automatised sensors.

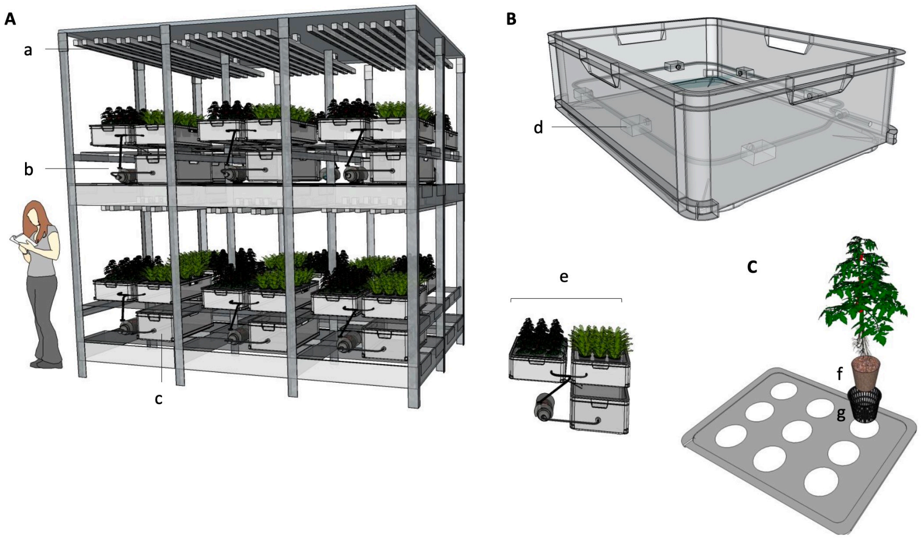


Figure 33: Detail of the high-pressure aeroponic system developed at ESTEE.
A: Overview of two floors consisting of 3 cells each. A cell consists of: 8 Philips GreenPower LED lamps (a) and a pump on each side (b) to dispense the contents of a nutrient solution tank (c) into two aeroponic trays. B: Each tank is composed of 6 low-pressure nozzles Ø 0.3 mm (d) which mist the nutrient solution. Two aeroponic trays and their nutrient solution tank are coupled together in closed loop, allowing the solution to be recirculated (e). C: Plants are supported by their stem in a non-organic substrate (f) in aeroponic baskets (g) allowing the roots to grow freely (g) in order to capture the nutrients, present in the misted solution. Source: Anne Cousin, Msc thesis (UTC, France) at ESTEE, 2018.

SP1 greenhouse surfaces for food production and air revitalisation is of 40 m^2 per crew member (CM) (80 m^2 in total). The generated waste for two CM per day is of 91 litres of liquid waste (88 litres of grey water and 3 litres of urine), 300 grams of solid waste (faeces) and 8 kilograms of edible an inedible biomass, as well as 3.5 kilograms of carbon dioxide.

Ambient temperature and humidity levels can be customised in each greenhouse and crops are grouped in the most appropriate one for growth optimisation.

Table 10 shows the nutritional data related to the 14 initially selected crops for SP1 greenhouses: wheat, soybean, sweet potato, pea, rice, bean, lettuce, spinach, tomato, chard, radish, red beet, strawberry, basil and parsley.

Crop	Energy (kcal)	Protein (g)	Fat (g)	Carbohydrates (g)	Water (g)	Yield rate (g.FW.m^{-2}.d^{-1})	Daily requirement (g FW.d $^{-1}$)	Area required (m^2)
Bean	31.0	1.8	0.1	7.1	90.3	65.2	782.1	12
Wheat	339.2	13.7	1.8	72.6	10.3	25.1	225.5	9
Soybean	446.2	36.5	19.9	30.2	8.5	5.4	48.9	9
Potato	77.0	2.0	0.1	18.4	79.4	360.0	4320.0	12
Sweet Potato	85.7	1.6	0.1	20.2	77.4	160.3	962.1	6
Pea	341.1	24.6	1.2	60.4	11.3	7.6	68.2	9
Rice	358.0	6.5	0.5	79.0	13.3	14.6	131.4	9
Radish	16.0	0.7	0.1	3.4	95.7	183.3	183.3	1.0
Lettuce	14.0	2.0	0.1	2.0	90.0	146.0	292.0	2
Spinach	23.0	3.0	0.3	3.7	91.3	81.1	730.0	9
Tomato	18.0	0.9	0.2	3.9	94.6	258.7	776.2	3.0
Peanuts	567.1	25.8	49.2	16.1	6.5	2.5	7.4	3.0
Strawberry	32.0	0.7	0.3	7.7	90.8	241.6	724.7	3.0
Swiss Chard	18.9	1.7	0.3	3.6	92.8	134.6	403.9	3.0

Table 10: Basic nutritional data of selected crops for 100 g of edible biomass.
FW: Fresh weight. Yield rates were adapted from Hu et al., 2009 and NASA, 2015 Life Support, Baseline Values and Assumption.

Figure 34 compares the different growth cycles of the selected cultivar within the HPA system.

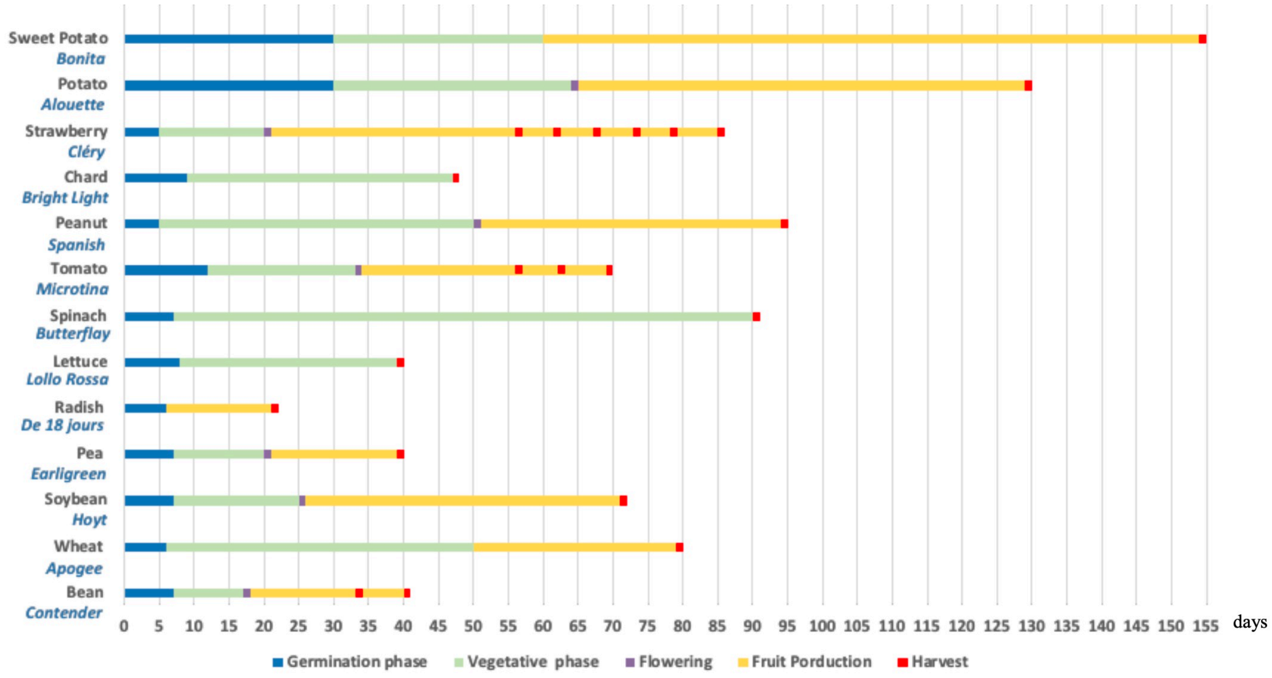


Figure 34: Growth cycles (in days) of the selected cultivars within the HPA system.
Source: Anne Cousin Msc thesis at ESTEE, 2018.

Typical required data for crop production are shoot height, productive cycle, pollination type/time, plant density, edible biomass per plant, shoot and root biomass or seed harvest index[555].

If the initially planned SP1 diet is not completely balanced as it is short in fat, it still offers an good balance of inorganic micronutrients. If the nutrient contribution of certain foods (e.g. soybean, peas, radish, lettuce, peanuts, strawberry) is minimal, the food production capacity is based on technologies that can be reused on other crops presenting higher or complementary nutritional values. Moreover it provides good variety for cooking. Macronutrients coverage is planned to be reached through dried meat and olive oil embedded into the closed habitat at mission start.

In parallel, other alternatives of simplified food production strategy for the SP1.X series (see below) have been assessed based on just two crops, wheat and hemp for bread production (Ameye 2018). Wheat is an important staple crop for NASA (Wheeler 2017) and ESA (Stasiak et al. 2012) which contains a high amount of carbohydrates and fibre. Its advantages include cultivation with easy maintenance and coverage of nutritional needs. Hemp grains contain significant amounts of omega-6 and omega-3 fatty acids, high-quality protein and significant amounts of Fe, Mg, P, K, and Zn. A heightened interest for hemp as space crop is to be noted (Carpenter 2018), connected to its numerous applications as food (hemp grains), pharmaceutical (cannabinoids), personal care products (fats and waxes), root substrate in hydroponic systems (fibres), food and beverage flavouring (terpenes), fabrics, rope, and paper (fibres), building insulation, hempcrete (fibres) and even hemp plastic (fibres). In terms of diet, a daily bread portion of 570 g of wheat and 161 g of hemp grains per crew member per day would achieve a perfect balance of macronutrients. Still, certain elements such as Ca and Na are lacking and must be added to diet, so ideally they should be recovered separately before reaching plants. Organic micronutrient (e.g. vitamin) coverage should not be a concern, as those can be covered by supplementation (and subsequent oxidation of excess in wet air oxidation). Finally, such simplification would clearly produce an extremely monotonous diet, even if bread-based diet is deeply rooted in human history. Nevertheless, this simplified diet alternative has many implementation, logistics, and cost optimisation advantages for short duration closure campaigns.

13.2.1.2 *Waste management*

The SP1 module 3 (Figure 35) is dedicated to waste management.

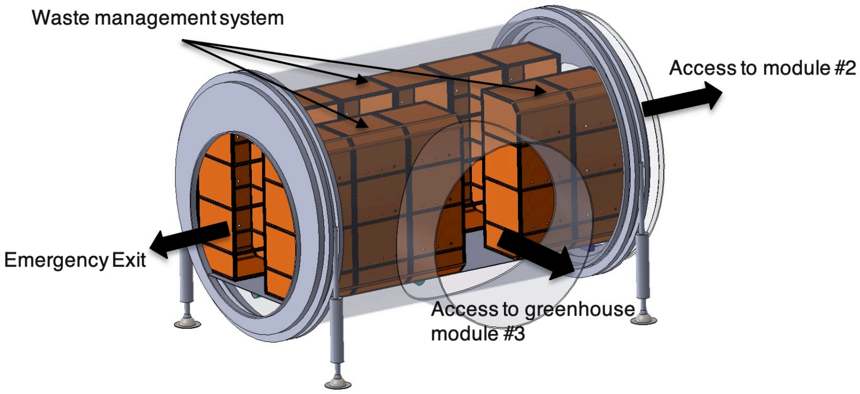


Figure 35: Inside view of the module 3 fully dedicates for waste management.
In the middle of the module, a door provides access to the greenhouse 2. On one end of the module, An emergency exit is located at one end of the module. Source: ESTEE, 2018.

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[555] Cf Annex A-§8.3.1.

SP1's waste management system (WMS) processes all the metabolic waste generated by SP1, namely: inedible crop biomass; grey water; urine; faeces; and miscellaneous solid waste including hair; finger- and toenails; sweat, saliva, and mucus solids; skin cells; skin oils; clothes dryer lint; and household dust. It should be noted that non-metabolic wastes (e.g. paper, feminine hygiene products, gloves, tape, external food containers, equipment waste) are not processed by the WMS, as the materials in these wastes are external to the SP1 material loop. Outputs from SP1 modules include: technical water for use as potable water and for plant irrigation, clean air for breathing in addition to O_2 from photosynthesis, CO_2 from organic carbon oxidation for photosynthesis; and inorganic nutrients for plant fertilisation. CH wastewater comes mainly from: the inhabitants' personal hygiene water; the inhabitant's urine; water used to wash clothes and dishes; condensate from the habitat's humidity and temperature control system; the chemical process for reducing the CO_2 produced by air revitalisation systems; phase change water from waste stabilisation and fecal desiccation; and experimental and laboratory water (evapotranspiration from experimental and food-producing greenhouses).

The objective of the WMS is to transform the above wastes to the following resources: technical water for use as potable water and for plant irrigation; clean air for breathing (in addition to oxygen coming from photosynthesis); carbon dioxide from organic carbon oxidation for use in plant photosynthesis; and inorganic nutrients (e.g. salts of nitrogen, phosphorus, and potassium) used for fertilisation of the greenhouse plants.

The WMS relies on physical, chemical, and biological processes to achieve its objective, and works as follows:

- a membrane bioreactor (MBR) receives grey water (from habitat sinks, showers, and washing activities). Part of carbon and nitrogen in these waste streams is oxidised, while another part is converted to microbial biomass;
- the treated effluent of the MBR is separated into a liquid and a solid stream via membrane filtration. Nitrogen salts are further separated by the liquid stream to be used as fertiliser, while the filtrate is used as the source of potable water;
- the source-separated urine is treated through nitrification via another MBR (Figure 36). The nitrified effluent of the MBR System is pumped to the liquid effluent collection tank. The residual organic carbon is oxidised via the wet air oxidation (WAO) unit. The advantages of the WAO unit are high conversion of organic carbon into carbon dioxide, no oxidation of nitrogen into N2 and full capture and separation of carbon dioxide. However, the process is complex, rather expensive and energy intensive;
- the solid stream of the MBR is mixed with the other solid waste streams (shredded inedible crop biomass, faeces, and the miscellaneous solid waste mentioned above), and then enters the WAO reactor for complete wet combustion of the waste organic matter (including ligninocellullosic material) to carbon dioxide, water, inorganic salts, and unused air;
- the liquid effluent of the WAO is recycled to the MBR for polishing. The solid (salt) effluent of the WAO is used for plant fertilisation. The gas effluent of the WAO contains carbon dioxide which is captured, compressed, and stored for future release in the greenhouse. The rest of the gas effluent undergoes catalytic polishing to be available as breathable air;
- the excess of biomass of the MBR effluent is separated by the ultrafiltration system, and is further pumped into a waste feed tank;
- the air management system regenerates airflows containing air pollutants, including odour, via a specific effluent gas catalyst unit.

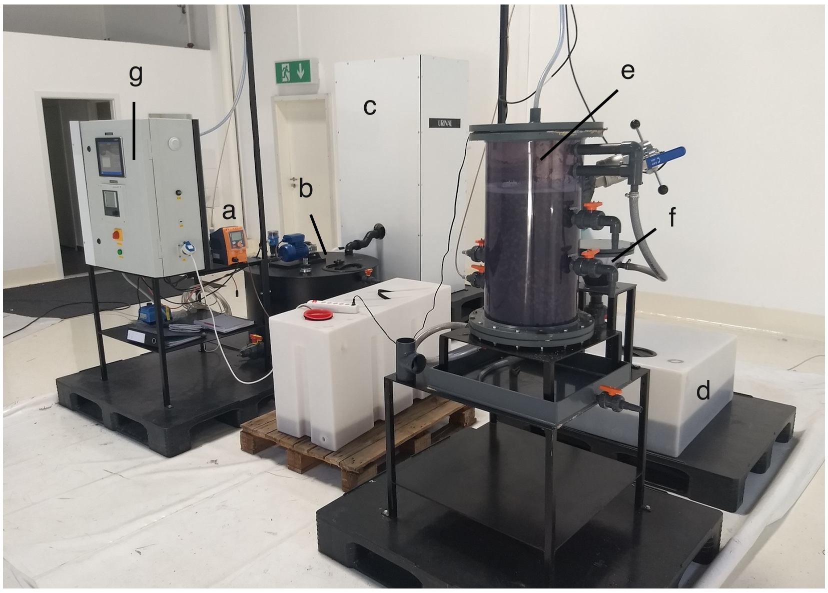

Figure 36: Nitrification unit prototype.
Nitrification system prototype developed by ESTEE for further integration into SP1. The system is inspired by a technology developed at EAWAG[556], and is a typical example of an essential technology approach. The components design is based on low tech and simple but robust, as well as cost-efficient equipment such as: (a) pump with rotameter and data logger, (b) urine storage with air humidifier and aeration pump, (c) urinal, (d) nitrified urine storage (e) nitrification reactor, (f) sludge sletter and (g) command control. Source: ESTEE, 2018.

13.2.1.3 Water production

The water production unit is placed in the SP1 module 2 (Figure 37).

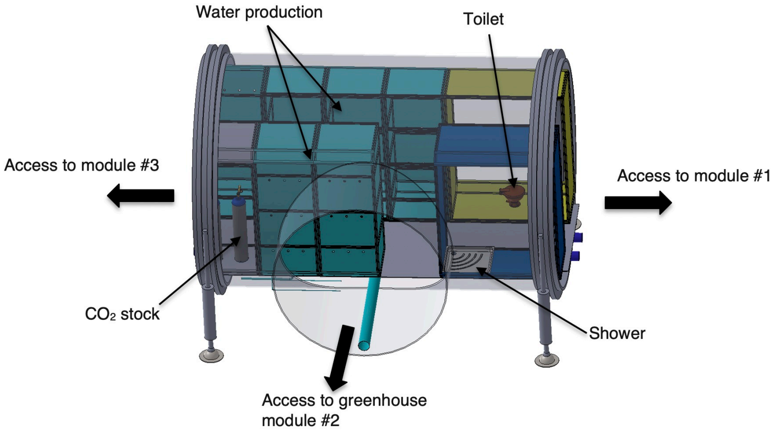

Figure 37: Inside view of SP1 module 2.
Module 2 includes a shower and a toilet. A door to access to the greenhouse module 2 is installed in the middle. From one side, the crew can access to the SP1 module 1 and to the SP1 module 3 from the other side. Source: ESTEE, 2018.

This unit will allow to treat the filtrate leaving the MBR from the WMS. Water resulting from this treatment provides potable water, clean non-potable water for specific uses (toilets and laundry) and hot water.

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[556] Cf Annex A-§7.3.

To achieve its objectives, the designed equipment offers the following functions:

- the greywater generation equipment (tap, sink, shower);
- the plumbing system connecting this equipment to the WMS.
- the water treatment system (WTS), which will include a separation unit and polishing unit: a microfiltration step will allow to separate solids from the filtrate leaving the MBR, separated solids will be given to the WMS. A subsequent ultrafiltration treatment refines the filtration process and then a polishing unit ensure water potability through a final water disinfection;
- two storage tanks of 100 litres, offering a reserve respectively for the potable water and clean non-potable water;
- the plumbing system to connect the WTS to the different points of use (potable water distribution network).

13.2.1.4 Core habitat

The core habitat of SP1 is composed of a module for living space with two private rooms and an exercise place (Figure 38) and a technical space with laboratory, stock, kitchen and laundry (Figure 39).

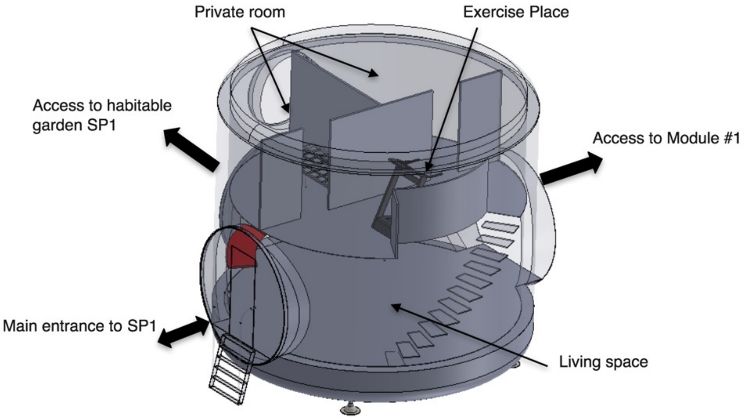

Figure 38: SP1 core habitat: living space with private rooms and exercise place.
Source: ESTEE, 2018.

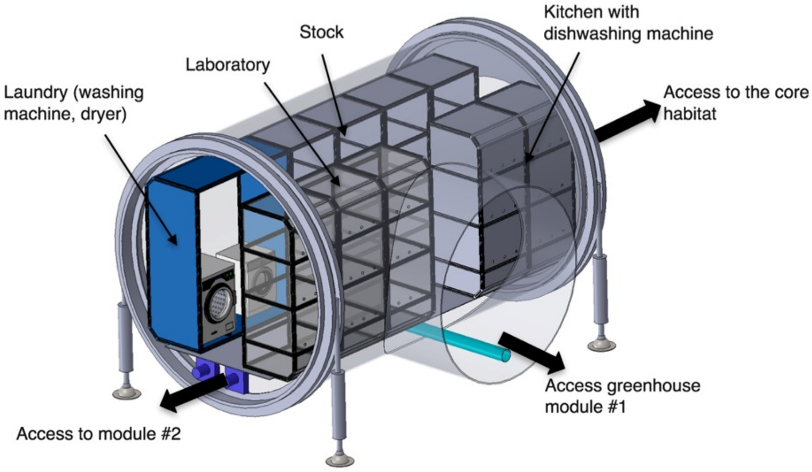

Figure 39: Inside view of SP1 module 1.
Technical space with laboratory, stock, kitchen and laundry.
The laboratory is the area where to prepare the harvested plants to eat them. Source: ESTEE, 2018.

The storage is mainly in SP1 module 1 (Figure 39) to stock the harvested plants and the food prepared by the crew. A CO_2 storage is also included in the module 2 (Figure 37).

The core habitat function also includes all the structures and the envelope of the CH, as well as human-machine interface between habitat and its inhabitants (habitat users).

As an ACE demonstrator, SP1 is designed to be as much as possible Mars-compatible in terms of confinement and isolation for a relatively long period of time as further discussed below[557]. Therefore, the design of the core habitat gives importance to comfort, ergonomics, and space optimisation[558], in order to keep well-being at its core.

13.2.1.5 Habitable garden

SP1's habitable garden (Figure 40) is a nature-like space, which can also serve as a carbon buffer through biomass growth. It contains several species of plants, including creepers, in order to mimic a natural vegetal environment and its biodiversity, and thereby provide a relaxing environment to the well-being of the crew in an otherwise highly artificial and technology-cluttered environment. It also brings together a fountain, to benefit from the quieting presence of running water, and to increase humidity rate in the air if needed. Sound is also carefully designed, through the help of a 3D sound system scattered in several speakers across the space, to increase the quietness and relaxation power of the garden. Plant growth over time acts as a transient carbon storage unit. When needed, plants can be trimmed to feed the WAO unit, and increase the CO_2 available in the habitat atmosphere.

The habitable garden has only one door, and is accessible directly from the core habitat module. It is set in a mostly opaque truncated icosahedron structure. The windows of the core habitat rooms have a view on the habitable garden to allow people to see this nature-inspired space from above regularly through the day.

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[557] Cf §13.4.

[558] Cf §13.3.

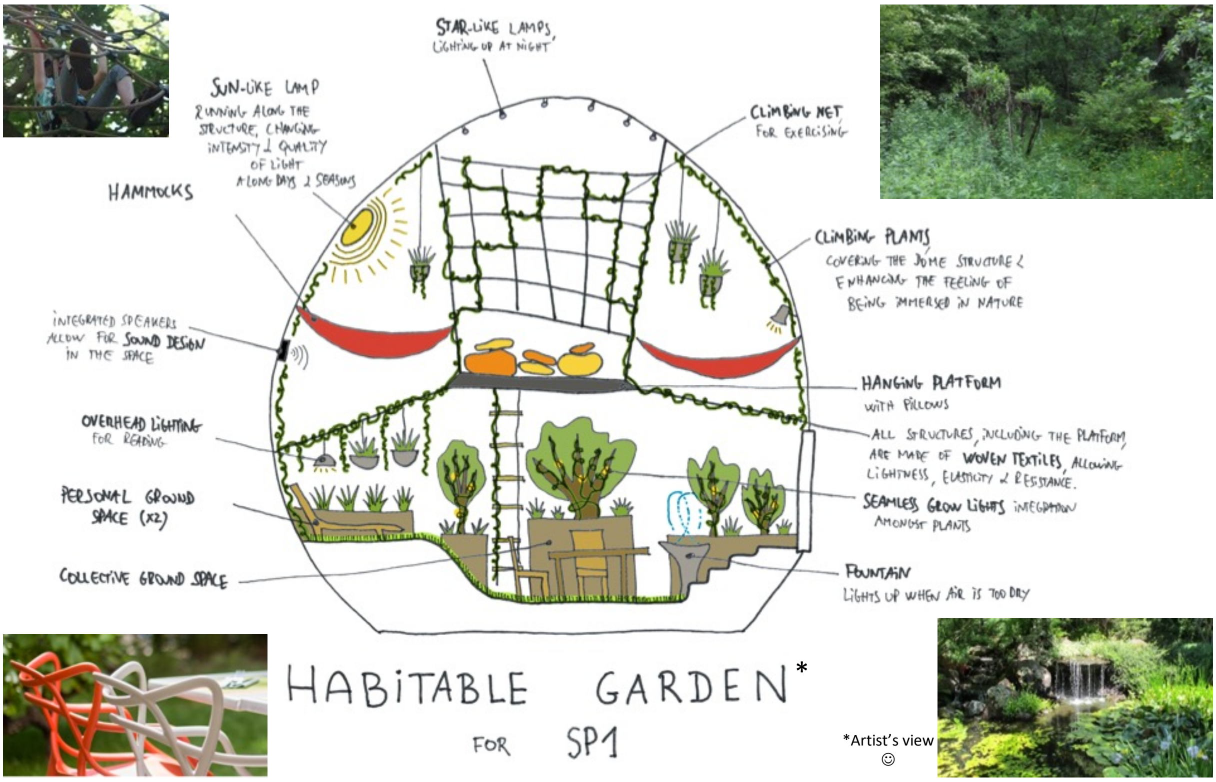

Figure 40: Artist view of SP1 habitable garden
The habitable garden integrates a collective ground space, with a table and two chairs, for the crew to spend some quality relaxing time together. A similar collective space is set on a hanging platform, with pillows, accessible through a rope ladder. In addition, it includes two personal ground niches, with comfortable sofas, where crew member can spend some quiet time on their own, as well as two hammocks. A climbing net makes use of the vertical space for some soft exercising. Lighting is carefully designed to mimic natural light, and allow plants to grow. A sun-like lamp, inspired from luminotherapy devices, runs over the ceiling of the garden as the sun would do over the day. Some star-mimicking lamps create an artificial night sky during night time.
The potential vegetal species and communities of the habitable garden notably encompass: shade-liking plants; climbing plants (including edible and medicinal plants, as well as colourful leaves and flowers); groundcover resisting high-stepping stress; perennial and annual plants polycultures (including edible and medicinal plants); plant guilds – matching plant-based ecological communities with various functions – based on dwarf fruit trees. Source: Michka Mélo, ESTEE (2018)

13.2.1.6 System management

With their respective specific needs (e.g. in CO_2, O_2, water inputs/outputs), each function of SP1 is independent and has its own control system. More specifically, a master-slave architecture is used for SP1 system management (Figure 41), with a master, as main controller, that coordinates the technical unit (the 'slaves') requests to ensure their proper levels of inflows and outflows. The master also treats the potential alarms coming from the slaves.

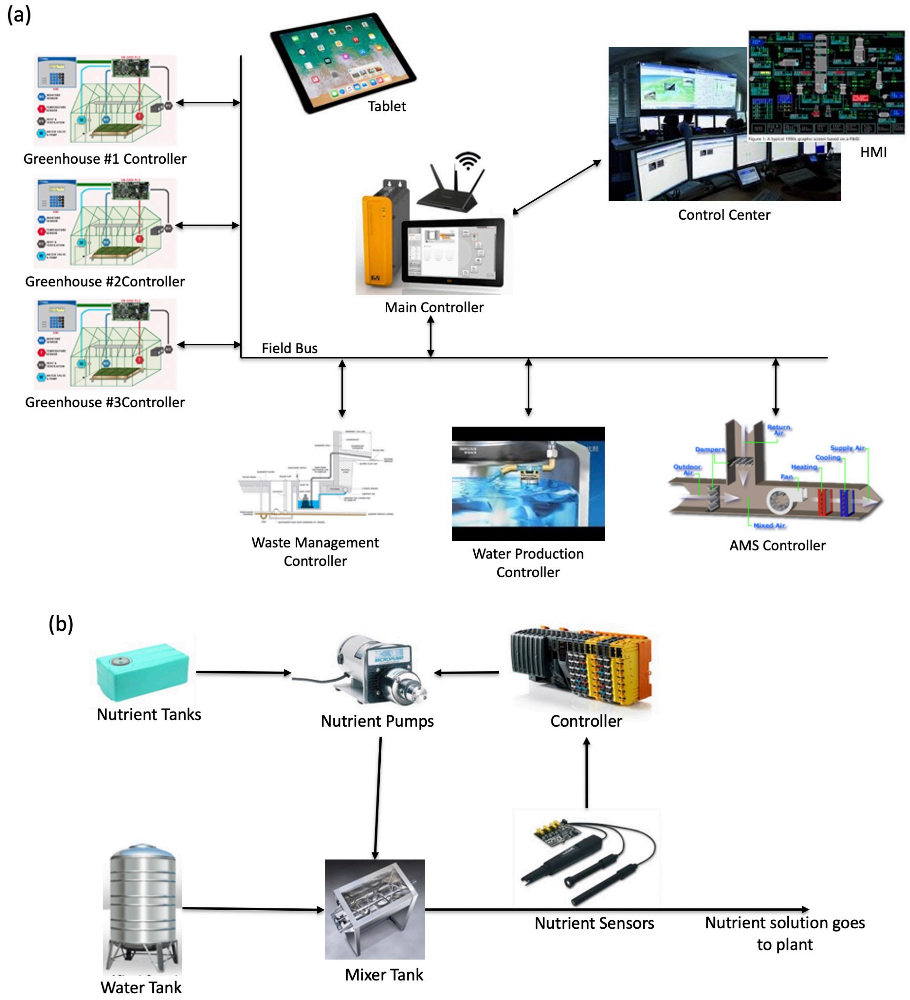

Figure 41: Slave Architecture for SP1
(a) SP1 command and control logics. The values of the sensors placed in the different environment can be visualised and influenced from Human Machine Interface (HMI) inside the demonstrator, as well as in the remote control centre. (b) Control of nutrient subcontroller (example). Source: ESTEE, 2018.

Design of SP1 was assisted by modelling (steady-state and dynamic) of all processes in the prototype, including chemical and biological reactors, the crop production unit, mechanical systems (e.g. hydraulic, HVAC), and electrical and control systems. Modelling and simulation approach were performed with the EcosimPro software[559] from EA Internacional, which is the standard tool used by space agencies for the simulation of LSS (Figure 42). Such model-based design can be used to predict system behaviour under range of conditions, optimise system and component performance, and reduce trial-and-error approaches, thus offering lower development and operation costs, increased system reliability and reduced operational risks.

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[559] EcosimPro webiste: www.ecosimpro.com

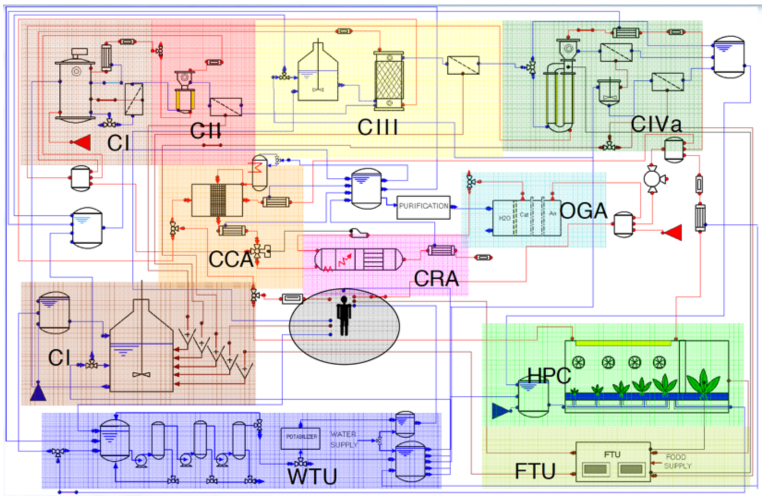

Figure 42: EcosimPro simulation of MELiSSA loop. Credits: EcosimPro.
Using one of the standard tools of ESA for LSS analyses makes it possible to make preliminary design, trade studies and mass/energy balances. NTE has collaborated actively with MELiSSA using notably EcosimPro for the preliminary design of a LSS for a future Moon base providing 100% air closure, 90% water closure and up to 40% food production in a second step (Viedma 2008). The above scheme shows the MELiSSA compartments and subsystems that were simulated in the study. Credits: NTE (MELiSSA partner).

Figure 43 shows a simulation of a cabin air management system using EcosimPro and Figure 44 the response to crew metabolic activity in terms of cabin CO2 level, temperature and humidity.

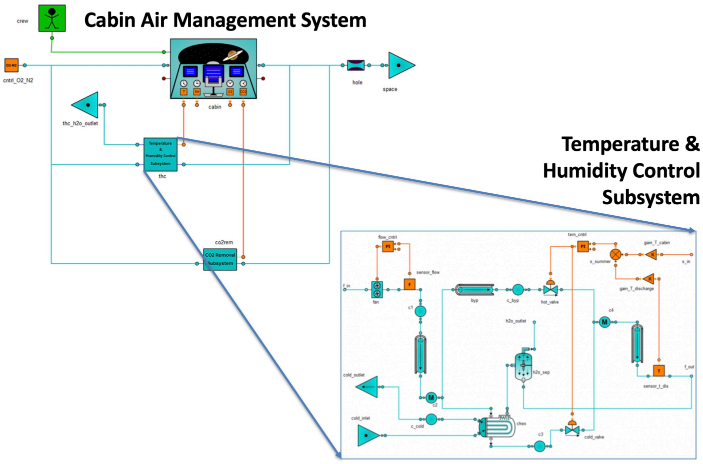

Figure 43: Simulation of cabin air management system using EcosimPro. Credits: EcosimPro.

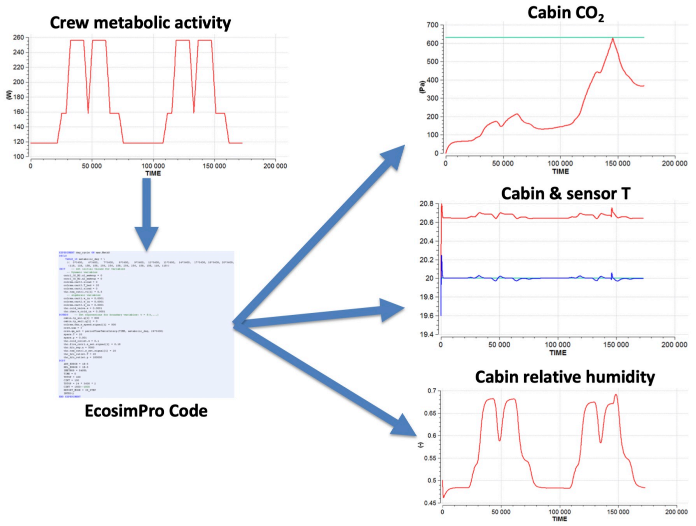

Figure 44: Simulation of air management system in response to SP1 crew metabolic activity.
The response to SP1 crew metabolic activity in terms of cabin CO_2 level, temperature and humidity was simulated by using EcosimPro code. Source: ESTEE, 2018.

A safety concept, with a risk analysis and a risk mitigation will be set in place for the CH demonstrator, compliant with Swiss regulation or any country hosting SP1.

13.2.2 SP1 roadmap

If a MELiSSA-type ALSS has been used as a guideline for Oïkosmos programme, another variant of an ACE has been conceptualised through SP1. As a ground-based simulator for conducting and channelling CH research, the prime objective of the ESTEE prototype is to demonstrate the feasibility of closed-loop operations in a minimal habitat. Figure 45 shows a simplified process flow diagram of SP1 with the above-described functions.

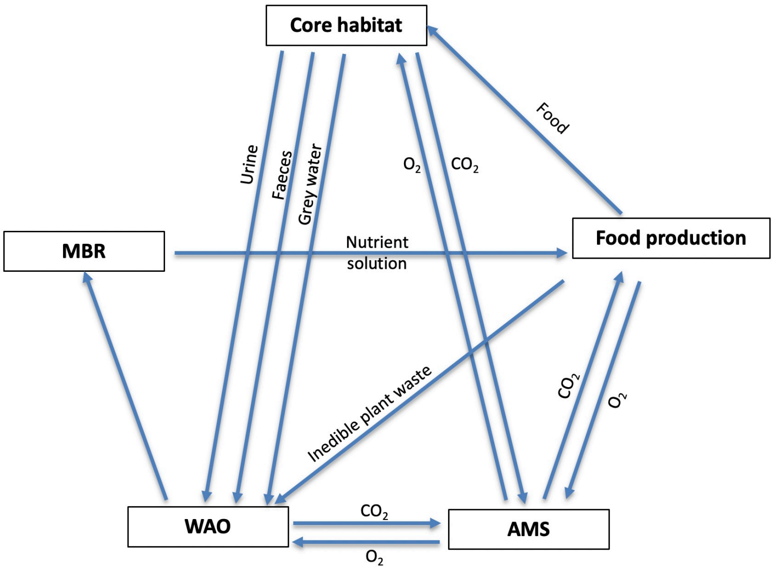

Figure 45: SP1 simplified process flow diagram.
MBR: membrane bioreactor (nitrification reactor), WAO: wet air oxidation, AMS: air management system. Source: ESTEE, 2018.

Since late 2018, a stepwise approach has been pursued for SP1 implementation plan aiming at optimising the significant cost of development.

Figure 46 shows a possible SP1.X series projection that has been roadmapped for a progressive integration of various ACE functions.

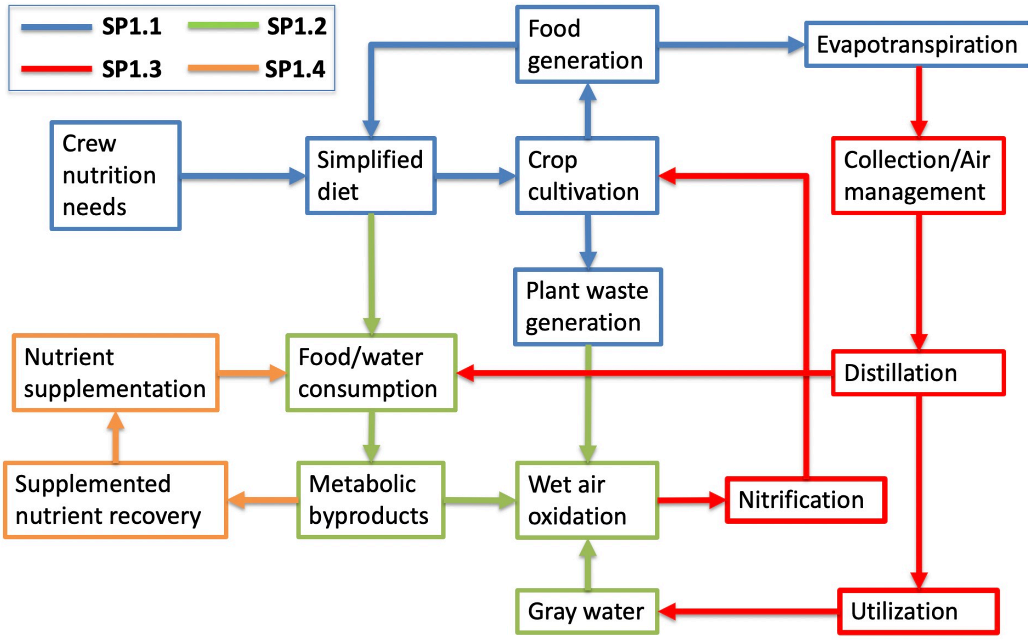

Figure 46: SP1.X series roadmap.
In this example, SP1.1 starts with plant production unit to supply a simplified diet to the crew. SP1.2 adds food and water consumption and gray water treatment and other organic waste recyling through wet air oxidation. SP1.3 further includes nitrification and air management. Finally, SP1.4 integrates nutrient recovery from metabolic byproducts, notably to provide food supplement. Source: ESTEE, 2018.

On Earth, an ACE simulator makes it possible to loop material flows and monitor the global processes of a miniaturised ecosystem with accelerated biogeochemical cycles for the main organic elements. Thereby, SP1 has been scaled to reduce the size of a human LSS to the minimum, while keeping a certain level of comfort. Therefore, the fundamental challenge of a CH design process relies on the technical choices and trade-offs for dosing and combining ingredients for material loop closure and life support features, namely sustainable resource management, user-building symbiosis, connectivity, adaptability, (bio)safety, modularity, robustness, and for space analogue habitat, space applicability, at least at subsystem level. Even if miniaturised, SP1 can be considered as a mesocosm[560], characterised by the following features:

- average size: larger than a test tube but smaller than the earth and most natural ecosystems
- highly confined;
- better defined spatial limits;
- intermediate biodiversity with many different types of organisms (humans and superior microorganisms and plants) on more than one trophic level;

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[560] Cf §3.1.

- the ability to induce organisms to interact thanks to highly controlled connections of flows between compartments;
- high level of control over inflows and outflows, giving researchers a free hand in setting some or all of the testing environment parameters (relative humidity, temperature, pressure, CO_2 concentration, level of pollutants, etc.);
- can be used to run short-, medium- and long-term experiments;
- a large number of sensors and other equipment to monitor and regulate key parameters;
- monitoring and follow-up of crew behaviour and psychosociology.

With SP1, ESTEE develops an ACE demonstrator that initially emancipates from the constraints of the traditional LSS roadmap of space agencies. The bottom-up approach apprehends a progressive material loop closure starting with low to medium technology readiness levels (TRL 3 to 6) as an intermediary step toward ESA and other space agencies ground LSS simulator such as MELiSSA pilot plant (MPP) and FIPES (Figure 47). Initiatives such as SP1 are geared to accelerate the preparation and financing on Earth of manned space missions. In particular, the prototyping activities around SP1 aims to fit in an adapted ESA roadmap through a public private partnership.

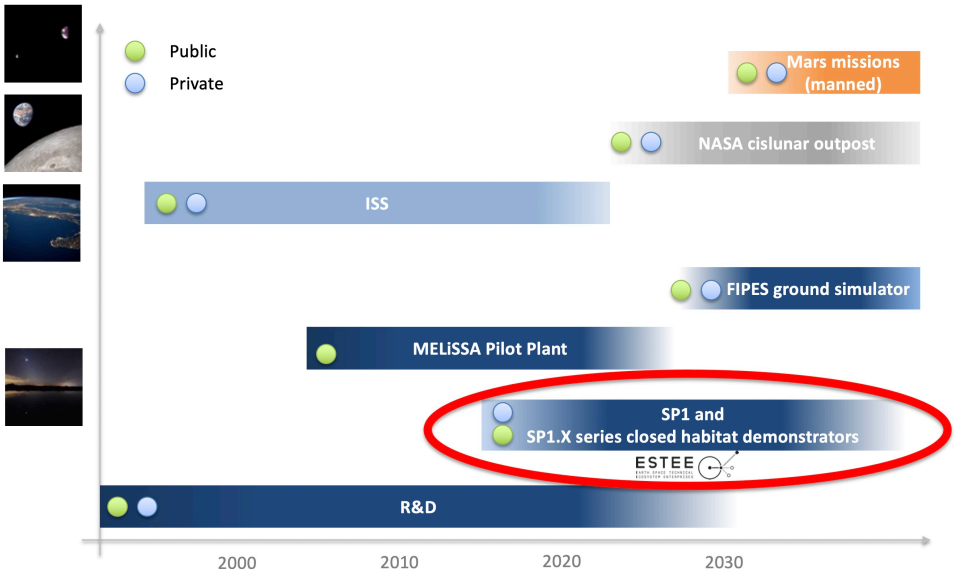

Figure 47: ESTEE prototyping activities within ESA roadmap for manned missions to Mars.
Most space agencies develop a long-term roadmap for ground simulation of LSS with humans, especially as they are working on higher TRLs compared to the ones of SP1. Nevertheless, one can consider that there is nowadays a clear need for an integrated CH demonstrator such as SP1, in order to enhance the preparation and financing on Earth of manned space missions. ESTEE envision to finance SP1 and to team up with public institutions thus building a public private partnership. Dates are only indicative. Source: ESTEE, 2019.

The technology integration for increasing closure of SP1 is considered gradually. It envisages the appearance of successive constraints adding up as the habitat becomes miniaturised in a closed-loop fashion, starting with air volume diminution, water content reduction, and optimisation of surface for food production, and finally downsized organic waste oxidation. With this approach, even as an ACE characterised by lower TRLs compared to MPP, SP1 can still strive for maximised loop closure level and closedness. At global level, SP1's TRLs for treatment processes are as follows: physical processes:

TRL 6 (membrane separation); chemical processes: TRL 4 (wet air oxidation) and TRL 6 (catalytic conversion); and biological processes: TRL 5 (bioreactor for carbon oxidation and nitrification).

As a pioneering initiative toward material regeneration, SP1 value proposition (e.g. unique selling proposition/'USP') is about actively participating to the space adventure in the framework of the preparation of the next steps of human space conquest. Future SP1 simulation campaign is about experiencing a Martian life inside a space compatible CH demonstrator, a technological platform with a miniaturised ACE, fully integrated within a self-sufficient, autarctic, off-grid and safe habitat. Apart its use as a testbed for ACE/LSS experimentations, SP1 being modular and mobile, it can be disassembled and relocated, and thus rented or sold.

The combination of technologies to be integrated in SP1 aspires to face some of the major challenges for a future expansion of Earth-based applications of ALSS, such as:

- technology development for waste valorisation, such as for removal, retention or degradation of inedible biomass;
- increased nutrient separation/recovery technology (Figure 36)[561];
- investigation of microcompounds and trace elements behaviour in closed systems[562];
- sensors for accurate health and environmental biomarkers measurements and near real-time monitoring[563];
- down-scaling to small waste(water) treatment and food production units and applications to closed and confined systems[564].

In this context, it is to be noted that compared to space agency ground simulator for space ALSS (ie. FIPES), a CH demonstrator such as SP1, that is driven by a private initiative, may be more easily connected to the implementation of the synergistic R&D Oïkosmos programme and thereby may present a more direct relationship to the development and commercialisation of terrestrial solutions[565].

In addition, the assessment of legal and regulatory environment of SP1 experimentations will highlight the compliance requirements depending on the context of uses. The same approach will be done for the assessment of biomedical and ethical aspects connected to the future establishment of crewed closure campaigns[566].

The SP1 project will be self-funded by ESTEE with a total budget of 10.9 million CHF (development costs only, excluding operational expenditures). The next step will involve its construction in the ESTEE facility in Bussigny, Switzerland, once the funding will be secured.

From 2021 onwards, for cost-optimisation purposes, the technology integration will be done in reduced size, in a closed chamber, namely the Scorpius Laboratory Prototype 1, that is shortly introduced hereafter.

13.2.3 Scorpius Laboratory Prototype 1 (SLP1)

Scorpius Laboratory Prototype 1 (SLP1) uses microalgae for air revitalisation, combined with other LSS

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[561] Cf Annex A-§7.4.2 on MASSTER proposal.

[562] Cf §8 on BELiSSIMA project.

[563] Cf §9 on SUMIT projects.

[564] Cf Annex I on SCIMA project.

[565] These Earth-based applications are further discussed in §14.2.

[566] Cf Annex A-§11.2.

features in a minimal closed chamber (Figure 48). As mentioned earlier[567], for a long time, microalgae are known to offer a number of benefits to support long duration manned space exploration. When integrated to ALSS, they can provide nutritional value (high content in proteins, lipids, essential amino acids and vitamins), capacities for organic waste treatment (urine valorisation), as well as for carbon dioxide fixation and oxygen regeneration through photosynthesis[568]. Compared to higher plants, microalgae possess higher growth rates and fewer cultivation requirements and generate less waste. Microalgae can also show resistance to harsh environment, for instance in terms of extremes in temperature, pH, as well as high salinity.

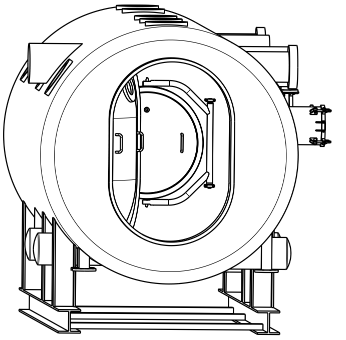

Figure 48: SLP1 closed chamber.
An hyperbaric chamber offers a sealed environment for SLP1-related technologies. Source: ESTEE, 2018

SLP1 is a simplified platform for the integration of closed-loop technologies, as shown in Figure 49.

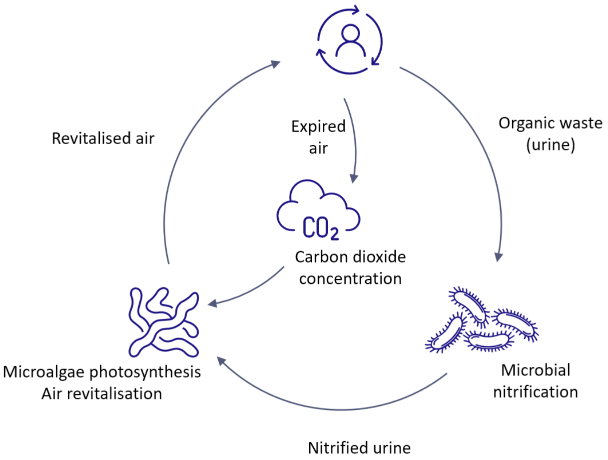

Figure 49: SLP1 simplified process flow diagram. Source: ESTEE, 2021.

Arctic and Antarctic regions have similarities to space, with their hostile and remote living environment. These locations can be used for hosting analogue facilities such as ACE and CH demonstrator, showing similar environmental (pollutant dissipation) and safety (no possible external on-site medical assistance) constraints, as well as geopolitical context ('colonisation') than those for future space travel and settlement.

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[567] Cf §4.2.2.

[568] Cf §14.4.2 on the uses of microalgae.

SLP1 is planned to become a first step towards the preparation of an underwater station in Arctic, which will be based on SLP1 technologies, for the next expedition of the French explorer Alban Michon, notably known for his documentary ‘Dip on Mars’ (‘The man who wanted to dive on Mars’)[569]. Named SEDNA, this expedition will rely on various LSS technologies to ensure a maximal autonomy and loop closure within an underwater station, from chamber research in ESTEE facility to long-duration missions in-situ.

The simulation of extravehicular activities through diving session will be at the core of the mission, using space-inspired diving suit, capable to reproduce conditions close to weightlessness in dark ice water. Specific safety and healthcare provision are required for the risk management of such space analogue (Posselt et al. 2021). SLP1 demonstrates the hostile environment around the underwater base which plays a role of a protective bubble for the explorer.

SP1 and SLP1 are sealed habitats designed to carry out cutting-edge experiments that will further our understanding of the engineering and sciences of ACE. Such high technological achievements would represent testbeds tooled for experimenting research activities from the Oïkosmos programme in real world conditions. These activities would include component testing and prototypes integration (for both emerging and proven technologies), health monitoring in CH, countermeasures to adjust environmental conditions, to cite just a few examples provided earlier[570].

As discussed in the next sections, designing an ACE demonstrator is practically about engineering a symbiotic, minimal and portable habitat for human beings, ensuring them an optimised habitability despite the strong constraints in place.

Initially, the systemic perspective prevails. Consequently, the role of ground demonstration will be of critical importance for offering realistic conditions for testing each mission system feasibility. Companies developing and operating such platform will be playing a facilitator role. Nevertheless, such multiple-technology platform is an enabling infrastructure rather than a marketable product per se. But it is composed of many technologies that have to reach ‘minimal viable product’ (MVP) stage to achieve the closure demonstration. In other words, an ACE ground simulator combines various and diverse MVP that composed each of its key subsystems for circularising material flows.

Therefore, space ALSS or terrestrial ACE supply chain will usually be organised in ‘tiers’ for each components and subsystems as ‘lego’ bricks for food production and waste valorisation. ACE/ALSS organisations will develop one or a combination of a few of these ACE/ALSS components (e.g. SUMIT toilet biosensors, microalgae reactor treating yellow water flow, nitrifying bioreactor for nutrient recovery, etc.).

Considering the above, SP1 and SLP1 aim to become cutting-edge scientific and technological platforms and innovative testbeds to challenge terrestrial issues related to sustainability and circular economy implementation[571], in the perspective of IE. Both are engineered to maintain a minimum level of essential functions and ‘services’ from the minimal biosphere enclosed inside them, that reveal their life support feature.

In a near future, and due to the complexity of interfacing each of these subsystems, other ACE actors will propose dedicated global services for a streamlined integration process of ACE components of tailor-made solutions responding to the host client system requirements. Apparently, big players such as SpaceX do not develop ACE/ALSS solutions and would need technology providers for their mission scenario.

These are some of the possible roles of ACE/ALSS company such as ESTEE in the years to come.

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[569] For a list of the expeditions of Alban Michon, see: https://albanmichon.com/en/expeditions-2/s (last retrieved on 10.05.2020).

[570] Cf §5 and Annex A-Part II.

[571] Cf §14.4.

13.3 Optimisation of the habitability of closed habitats

This section approaches the habitability of CH, as their technical requirements and user experience should guarantee a high system closure without compromising the user's comfort, ergonomy and acceptance, and the habitat's sustainability. It first explores the notion of human habitat (§13.3.1) and then the enhancement of comfort in CH through user-building symbiosis (§13.3.2).

13.3.1 Exploring the notion of human habitat[572]

When considering what we call 'habitats', different words and images are coming to mind. Often subjective, these mental representations are based on our own desires and memories, and marked by our cultures and traditions. As a matter of fact, the term 'habitat' being a rich concept, finding a universal definition appears to be challenging.

A habitat is first and foremost a space that individuals will occupy. Any construction is not called a house; take the example of a dam or a bridge. Moreover, a habitat is more than four walls and a roof, more than a patchwork of materials. Its occupants take possession of a space, a territory, more than a building. Granting oneself a place for living means having a stable location, a landmark, an anchor for being. As a living space, a habitat offers 'the capacity of everyone to be present in the world' (Paquot 2005). Furthermore, the absence of home means to be excluded in the sense of 'locked out', in a hostile and changing environment (Beauchez & Zeneidi 2018). Being 'locked in' resonates with a notion of safety and stability, which is connected to increased control and less unexpected change. Thus, a habitat gives the possibility to cut ourselves from the exterior world, more variable and risky. It represents a shelter protecting from outdoor risks such as weather exposure or predators. The recent lockdowns caused by the sanitary crisis of the COVID-19 pandemic are magnifying this shielding role, in this case for preventing cross-contamination from a viral pathogen. According to Chalas (2000), 'the habitat shall be perceived well beyond its capacity to shelter, even to protect and cannot be reduced to its functional dimension. It involves a relation between a place and its surroundings, between people and their relation to the world'. Beside this appropriation of its space, living in one's habitat is coupled to the time factor: a home cannot be somewhere we only pass through and implies spending time inside (e.g. for resting). There is a concern to feel not only secure but familiarised with the space. Finally, the notion of habitation is understood as a ritual practice of space, in everyday life. It refers etymologically to the term *habit*. Indeed, a habitat concentrates lots of our habits.

A quick look from a historical and sociological approach on the modes of habitability shows that what we value today is not what we valued yesterday, and most probably what we will value in the future. Serfaty-Garzon (2003) pointed out an evolution of our modes of thought: 'From middle of the Middle Ages to the end of the seventeenth century, private life and intimacy were confused with collective life.' Privacy and public life were not opposed as today. Yet, previously, 'At any hour, intimacy was unknown' (Flandrin 1976). During the eighteenth century, a new vision of privacy and a search for intimacy around a family feeling, the organisational, material and spiritual aspect of house had changed. In the modern history, and especially in the twentieth century, an idealisation of seeing a house as a shelter and a sweet private home, in a strong opposition to a public sphere has progressively taken place (Ariès 1986).

Nowadays, changes in our way of thinking living spaces came from the pervasive uses of new ICTs that progressively brought about a whole new form of exchanges and social relations inside the house, which transformed private and public spaces. On a material organisation level, we remain essentially on the same pattern of space (e.g. different degrees of intimacy according to different rooms). But on a meta-

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[572] This section adapts and complements excerpts of the work of Chloé Yvard during its 2017 ESTEE internship on 'a human-technical approach of the notion of habitat', under the supervision of Michka Mélo and Théodore Besson.

organisation level, a new sense of privacy emerged, as it is becoming less obvious that privacy is guaranteed by being cut off from public space. During the 1990s the Internet has been opened to the public and benefited from a spectacular diffusion so that 'new uses of new technologies had implied a major source of privacy challenge in terms of sharing of personal data (geolocation, preferences...)' (B. Rey 2012). Today's intense use of social networks (access to friends and family members, but also only acquaintances) can be opposed to previous recent practices before the World Wide Web era: 'the emergence of blogs or social networks that are full of information or documents (photographs, stories, friendships, tastes, appointments, activities) would have been private, even intimate, until the 1990s' (B. Rey 2012).

Through the current technological advances, what has become a 'smart habitat' now integrates more and more what were traditionally urban functions so that the distinction between private and public in our today's house is no longer possible as exemplified by Degoutin (2006)[573]. The same observations can be made on the recent evolution of the boundary between work and family life as per Rey and Sitnikoff (2006): 'Teleworking at home, based on the use of ICT, [...] redefines the spatial and temporal boundaries that have strongly structured the world of work.' This trend has been accelerated since 2020 with the pandemic due to COVID-19 disease. This is materialised by portable terminals, such as laptops, smartphones or tablets, having a 'private' appearance (personal property, mostly individual use, protected by passwords), but making a bridge towards public, and particularly from one's house. Now, the house is where we socialise ourselves, and also more and more often where we work. Kallipoliti (2008) described the design of self-sustaining habitats from an architectural perspective by means of 'a dissolution of the human body within the elements of the system through retroactive loops and material connections'.

These trends show that privacy is being redefined today within smart habitats. Inside what has become a space of privacy, a new sphere of intimacy and a new scale of isolation has been built through new technologies, thereby implying to create a private sphere inside private home. The same logic applies to CH, where technologies are ubiquitous, including the ICT ones. Just by considering that diet practices and excretions are constantly monitored and subject to near real-time feedback, mostly through human-machine interfaces, privacy with an inhabited ACE becomes extremely limited.

Using such technical solutions in a self-sufficient habitat prototype has to take the human variable into consideration, because any technical solution, even the most functionally optimised, is not always acceptable for the users of the building. Among the environmental issues affecting individual and group functioning in CH, ones can note a reliance on technology for life support and performance, and dependent human-human, human-technology, and human-environment interfaces (Häuplik-Meusburger & Bishop 2021). Balancing system performance, healthy diet, resources recovery and conviviality in terms of user experience and user interface is essential to approach the system in its totality. Comfort and user building relationship are therefore discussed in the next section.

13.3.2 Enhancing comfort in CH through user-building symbiosis

If survival, as well as the coverage of essential needs of its inhabitants are so critical in CH, it should not be its only finality. It is desirable for such systems to offer at least a gain of comfort to ensure a

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[573] According to Degoutin (2006): 'Inside the house have been reconstructed miniature functions normally public: cinema in the form of a home cinema, workplace in the form of a home office, hospital in the form of home-based care, restaurant in the form of prepared foods, museum in the form of art books, the casino in the form of online gambling, the corner coffee in the form of an *espresso* machine, shopping in the form of mail order, gymnastics club in the form of fitness machines, a concert hall in the form of a hi-fi stereo, public transport in the form of a car, post office in the form of an e-mail, social events by online chats, closed house in the form of call-girls and home masseuses, nature in the form of apartment plants, people in the form of telephone conversations, public baths in the form of own swimming pool.'

certain level of well-being instead of enduring the rigid conditions of the building.

Interestingly, the notion of comfort is a relevant bridge between technical requirements and human ones. Technically, today's building sector has greatly evolved by considering environmental management as a major concern. For instance, buildings progressively improved their energy efficiency through compactness, daylight use optimisation, interior organisation, using ecomaterials and renewable energy supply. For the latter, the market is mature and offers technical solutions for efficient ventilation, air conditioning, heating, lighting and hot water production. Moreover, houses can nowadays be built with a positive energy. Some of the latest advances in habitats comfort result in increased levels of automation (e.g. automation of roller shutters to optimise the solar heat gain or loss). However, as the concept of comfort is correlated with the user feeling of satisfaction with the environment, successfully meeting the objectives in terms of energy does not prevent numbers of building users to be dissatisfied with their comfort system at home. Keeping the roller shutter example, according to Nembrini and Lalanne (2016), 'a series of negative experiences of users, now become almost daily life/commonplace experiences at work: automated blinds implying users' eyes an erratic attitude, environments controlled to the extreme creating a feeling of 'enduring the building', or even going through a symptom called the 'Sick Building Syndrome' (…) because buildings tend to be drastically hermetic to the exterior environment due to energy-saving reasons (…) [and] nervousness caused by the arbitrary and alienating actions of the automatic blinds control.' This illustrates only one of the many aspects of human comfort in buildings, which also typically encompass thermal comfort, indoor air quality, lighting and acoustics (Schweiker et al. 2017).

In buildings, if the comfort felt by the user is the one that should matter in priority 'it is almost only the environmental objective comfort that is used in the architectural design process' (Nembrini & Lalanne 2016). Consequently, even if the temperature and ventilation are set as physically and energetically ideal, users are often dissatisfied and get round the comfort system by opening a window. Similarly, two people in a same room can feel satisfied and dissatisfied in terms of perceived comfort, as for instance the human thermal comfort depends not only on environmental factors (airflow, air temperature, air humidity, sun radiation, etc.), but also on personal factors (clothes being worn, level of physical activity, personal physiological characteristics). As demonstrated in the keynote speech of Prof. Lalanne at the ESA Closed Habitat Forum 2016[574], optimising the user experience in ACE precisely implies tracking the perceived comfort. In CHs even more than for classical building environments such as home or offices, the capacity for the user to influence the building maintenance provide a feeling of control that already improves the perceived comfort. The latter example shows that any CH demonstrator should be designed to optimise the perceived comfort by incorporating the user variability parameter and ensure that the building can adjust over its lifetime its physical measurements to human sensations. Thus, in the context of ACE, evolving in a sealed habitat has to allow the occupants to reinforce their relationship with the inhabited space. Consequently, an ACE demonstrator can be used to test if and how people could live and work in a sealed biosphere for extended periods. More than taking it over, dwelling a CH is about entering into some form of mutualistic relationship with the building, that is, experiencing user-building symbiosis: the building provides its occupants numerous services that are mutually beneficial, respectively in terms of life support feature and maintenance effort resulting into relations of reciprocal interdependence[575]. The user-building symbiosis relationship relies on the involvement of its occupants for setting the building parameters along a certain range of tolerance. A closed simulation facility, in its quality of habitat under strong constraints[576] and in view of the significant duration of the mission

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[574] Cf §10.1.

[575] CH can be envisoned as a web of interconnections between man and machine. For instance, the intranet of CH links machines, humans and devices like do web 1.0, 2.0 and 3.0. The same applies for the connection of CH crew and subsystems with the outdoor through internet. In that sense, CH uncover a successful kind of symbiosis between the biological and the electronic counterparts within a building, far from intrusive technologies such as implants or cyborgs.

[576] Cf §6.1.4 and §13.4.

campaigns, would have all interest to provide a certain level of comfort to its hosts[577], in order not to hinder the accomplishment of their operational tasks (from a professional point of view) and to guarantee a minimum of personal development for each crew member thanks to an adequate habitability (ergonomics, psychological conditions, fight against monotony).

A smart habitat is not a patchwork of connected appliances and equipment, it becomes smart if it enables something considered as smart. A seamless effort or decision-making step for the user is what matter the most[578]. Endowing the habitat with machine learning capabilities could help better understanding its users' behaviour patterns, leading to the proposition of possible actions to take in order to make the habitat use more sustainable. In this respect, technologies should advise users, such as rather doing this action and not another based on data building analysis, for the good of the house or ACE module performance (meaning saving resources for the future) with a visual information on the benefit of the action (such as a basic gradient from green to red for energy saving level). As a consequence, raising awareness can leverage the change of behaviour.

A fully CH case typically presents a higher user density, implying challenges in terms of interface and furniture design because the user-building interactions should be effortless and comfortable enough to the user. The occupants can be considered as part of the mechanics of the CH, and should be aware of their role within it, as well as of the impact of their own choices on the building sustainability performance. Whatever the degree of automation of the building system, dissatisfied users should be able to change the interface by themselves through 'end-user programming' to improve the habitability. In the end, the balance between technical requirements and user experience should guarantee a high system closure without compromising the user's comfort, ergonomy and acceptance. In other words, user experience is not about TRL, but what people can do with technologies.

If human factors and habitability are important topics for working and living spaces, they are obviously even more essential in an extraterrestrial context. In particular, observing that unfortunately the focus is still on building functional survival shelters and not living places, Häuplik-Meusburger and Bishop (2021) questioned what constitutes the space to live happily and productive in extraterrestrial environment. Among the most desirable characteristics of future living spaces are needs (Häuplik-Meusburger & Bishop 2021, p.162) for privacy and personal spaces, safety (feeling safe), outside viewing, as well as adaptability and adjustability to personal and/group taste/needs[579]. As their occupants live within a social environment that is confined, prisons are in some significant respects similar to planetary stations (Cockell et al. 2021).

Beside the comfort aspect, the long-term confinement in a sealed structure raises new challenges in terms of biosafety and for maintaining the ACE subsystems in routine operations, to cite just a few[580]. As a consequence, some of the ritual practices and habits become imposed to secure the functional activities in place, as per the space missions adage 'failure is not an option'. Indeed, in most cases, as

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[577] Häuplik-Meusburger & Bishop 2021, p.180: 'Over the history of space habitation, we can say that the more transient the occupants, the less emphasis or concern is spent on human comfort.'

[578] For instance, learning when to open and close windows and blinders to keep the house fresh in summer makes people not only know more but also like their house. The same would apply for optimisation parameters for plant cultivation, especially as it will be finally consumed by the user. Thus, the users can participate to the improvement of the energy consumption and plant production yield, and be rewarded through proper human-machine interfaces displaying the increase of building (modules) efficiency. In the end, such process simplifies certain aspects of the comfort-sustainability trade-off.

[579] Häuplik-Meusburger & Bishop 2021, p.162: 'In terrestrial conditions we can tolerate limitations and dissatisfaction of our living conditions for some time as there is a possibility to move out or change the environment. That will be different on other planets. Seems personalization of a living space will be important for inhabitants and groups will be more cohesive to survive and be productive.'

[580] Häuplik-Meusburger and Bishop (2021, p. 219) summarized the factors contributing to confinement: isolation from family, friends, the familiar social environment and alternative others; feelings of crowdedness; restrictions in going outside; limited and forced social contact with a small group; lack of stimuli leading to monotony and boredom with available environment and social contacts; and extreme artificiality and visual complexity of built environments leading to attentional fatigue.

for the space ACE, it is simply a matter of survival. A CH operates relatively independently, without being influenced by on-site external conditions, and with very little – if any – interactions with the neighbouring natural ecosystems in terms of material flow exchanges. Yet, being literally locked-in does not mean that the relation with the surrounding environment is secondary. Both the internal and external conditions have to be well monitored, and telecommunication with control centre, as well as with relatives, has to take place regularly. Moreover, the activation of countermeasures might be needed on a case-by-case basis. Telehealth aspect is particularly key to enable the crew to feel good enough inside in the long run. In particular, Oïkosmos Report described telepsychiatry-related topics and notably the remote monitoring of the crew psychological state, the psychosociology, as well as the psychophysiology of emotion and performance under extreme conditions[581].

Remotedness and isolation, together with confinement of human outposts are stress factors that can affect the psychological health of the members of the crew (Marcinkowski et al. 2021). Not to mention as well as the stress caused by the intense workload and the pressure for the mission success. In this regard, meals eaten in a CH should provide digestible, fresh and palatable food, and constitute a social moment that is crucial for the crew morale (Meusburger 2014).

The crew practices will be influenced by the self-sufficiency parameter itself, like with food production capacity. This latter aspect shall play a significant role for the user-building symbiosis of a CH demonstrator such as FIPES[582] or SP1[583]. For instance, by integrating technical solutions for empowering self-sufficiency, circularisation of the flows will produce food from individual waste which will need acceptance from the CH users. By exploring the fundamental relationships between humans, building and cultivated plants within an in-vivo experiment, such demonstration building will create new habits and routine operations, that is, new practices and experiences for which organisation of the crew life and time are crucial dimensions. For not enduring the building, the autonomy provided to its users should let them adjust to the practices created for them. Consequently, this means finding a trade-off between system performance, healthy diet and conviviality in terms of user experience and user interface. The technical way chosen for answering the functional specifications of plant production systems has to find a balance between the degree of automation (of the building) and the level of involvement of the crew for food production, e.g. for operating, maintaining, harvesting, storing, preparing and cooking leads to a food that is nutritionally rich, tasty, and produced in a sustainable way. The whole process necessitates that the building users have the capacity to combine roles of operator, farmer, gardener, cook, and consumer[584]. In this context, technologies user interface shall alert users not just about the detection of a maintenance problem. To avoid being perceived as a black box for users, user interface shall go further and indicate when and why the seeds germination will take place, which biological process is in progress or what are the nutritional values of a given food in cultivation, or of a particular prepared meal. For any information likely to interest the users: users being more aware will do better actions.

In summary, CH users have to care about the building they live in and develop a strong and empathic relationship with it. Simply to cope with the fact that they fully rely on it. Reversely, the CH has to offer the best possible user experience to its inhabitants, which will positively affect the perceived comfort.

As shown earlier[585], the notion of habitat has evolved over time. Further defining standard and norms of CH can contribute to shape the habitat of tomorrow. In this perspective, ESTEE pursued with ESA a TAS ('technology assessment') project[586], which aimed at paving the way towards the development of

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[581] Cf Annex A-§9.4.

[582] Cf §6.1.

[583] Cf §13.2.

[584] Cf Annex A-§8.3.1.

[585] Cf §13.3.1.

[586] ES-TAS 'Towards the establishment of a standard on closed habitat specifications' (reference 130046707), cf Annex H.

a standard for the appropriate definition of CH specifications, as a follow-up to the conclusions of the ESA Closed Habitats Forum in 2016[587].

Strengthening our understanding on the notion of CH from a human and social standpoints brings another perspective to a human ACE project, complementary to its technical and functional specifications. Indeed, a CH demonstrator is above all a project for humans. It cannot be only modelled, quantified or rationalised, as would do a purely technical approach. And humans should not be seen mainly as biological beings, physical entity or flow of energy, but rather considered as individuals living, moving, thinking, reacting, and socialising in and through the sealed space. In other words, the human parameter is required, and setting it aside would certainly prevent any closure campaign to be successful, and actually even ethically allowed. In addition, the dimension of the disposable time (Hanbury et al. 2019) of occupants should be considered as an element for optimising the sustainability component of living within a CH.

In conclusion, one cannot create and design a technology without thinking whom it serves. The same applies to a CH such as an ACE demonstrator. Developing a CH pleasant for dwelling in relies on a human-centred approach. As a user of the habitat, its occupants are not just biological bodies. As users, they are not only eating, drinking, sleeping, and excreting, but as well operating and maintaining the ACE itself, in a word, fully participating to the ALSS loops within the habitat.

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[587] Cf §10.1.

13.4 CH as a minimal habitat for self-sufficiency in the perspective of IE

In general, terrestrial habitats and their inhabitants are facing nowadays - and may in the future face even more - a reinforcement of constraints, which are admittedly less extreme than their space equivalents[588], but which are increasingly similar to them, for example in terms of criteria relating to:

- confinement: with urban environments presenting challenges linked to the small size and reduction in volume of the habitat;
- isolation and autonomy: in particular for elderly people, convalescents or those suffering from chronic illnesses living outside urban centres, which may present difficulties in accessing care;
- environmental conditions to which the inhabitants are exposed: in a context of increasing pollution, with issues related to air quality, climate change, etc.;
- increasing pressure on resources causing lack of availability for:
    - housing (buildings): during the construction (building materials), operation (energy supply) and renovation phases;
    - housing devices and equipment: during the manufacturing (use of ecomaterials), installation, operation (energy efficiency) and end-of-life management phases (durability, recyclability, potential for energy recovery and reuse of components, etc.).
- nutrients supply for the life – and survival – of the inhabitants, with issues related to the quality of water and food (presence of pathogens, bioaccumulation of contaminants or micropollutants); the availability and efficiency of resources for agricultural production, the quality of soils (dissipative losses of nitrogen and phosphorus);
- increased compliance requirements for environmental legislation and technical standards, and increased treatment costs: particularly in European countries (including Switzerland).

It was anticipated earlier[589] that these similarities between space and terrestrial habitats will continue to increase. These similarities can already be acknowledged in certain terrestrial sites evolving in extreme conditions, such as polar bases in the Arctic and Antarctic, submarines, sites hit by natural disasters or conflicts[590].

In any case, putting a habitat under a bell in a CH implies for its occupants to live under such strong constraints, since it would often combine the vast majority – if not all – of those listed above. In this sense, FIPES[591] or SP1[592] are emerging as minimal pilot facilities to prepare and adapt to a more constrained future, with conditions increasingly similar to those encountered in space systems.

CH could be defined as habitats doted of autarky and self-sufficiency for fresh food and potable water, in which resources can be recycled up to the point in which the material loop is closed, at least to some extent. In other terms, stored food supplies would not be enough in the long run, which implies that a certain level of food production has to take place within the habitat. Self-sufficiency for food and water increases the value of the available natural resources through bioregeneration, nutrient recovery and waste valorisation, and these circularisation processes become in return vital for the crew. By ultimately targeting integral recycling, which involves the recycling of the vast majority of the types and fluxes of human-generated organic waste, as well as water and atmosphere regeneration features, the notion of CH supposes that at some point, the habitat would be able to fully process and reuse its own material

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[588] Cf §4.3.

[589] Cf §6.1.2 and Annex A-§6.1.4.

[590] Cf §14.2.

[591] Cf §6.1.

[592] Cf §13.2.

outputs so that no more material inputs would be needed.

The challenges of CH are also considerable, ranging from the reliability of the equipment used to operate the ACE, to the omics evolution of the organisms involved, to the psychosociology of interactions between its occupants, the presence of sufficient technological back-ups automatic, or the maintenance of sufficiently stable homoeostatic conditions.

As a form of ACE demonstrator, a CH is a platform for studying natural science issues, generating knowledge from the biological, physical and chemical processes of the natural and man-made environment, as well as for modelling and understanding the dynamics of complex systems, and studying problems of system boundaries and scales.

In particular, a CH is setting boundary for a minimal habitat interfacing human with a hybrid combination of biosphere and technosphere elements, respectively the living organisms of the ACE and the technical hardware of the building. Such CH materialises the extreme case of industrial ecosystems discussed earlier[593]. Building a small-scale hermetic biosphere is thereby about being capable to engineer and embed a minimal ecosystemic unit within a minimal bioinfrastructure.

While crossing terrestrial boundaries, space travel through the immensity of the solar system implies somehow paradoxically to seal humans in very limited boundaries with few EVA possibility. From the perspective of IE, it is precisely the 'perception of limits' that must be taken into account, both on Earth and on Mars. In a base on the Red planet and more generally in space habitats, it is indeed not possible to 'cheat' with reservoirs and stocks due to very limited buffer capacity[594] – and this is much more obvious than on our blue planet – which makes it essential to develop highly efficient recycling systems[595]. Thus, there is an analogy between the 'draconian' Martian conditions and those that the Earth may face in the near future, in addition to some 'drastic' conditions already observable today (ubiquitous micropollutants, pressures on rare earths, etc.).

In this context, the 'Spaceship Earth' metaphor, popularised by Boulding (1966), and later one of favourite saying of Fuller (1969) for whom 'we are all astronauts' in his Operating Manual for Spaceship Earth, conceptualises our planet as a 'capsule', which is certainly immense, but which is continually shrinking, given the relative and absolute decline in the level of available resources. Taking literally this perception of the shrinking 'Spaceship Earth', CH demonstration aims at maximising the level of LSS services as well as the system mass reduction, within a portable and flyable ACE, that could ultimately be transferred and extended progressively on a planetary base.

Extraterrestrial environments are unforgiving, which tolerate no room for error, especially as inhabited LSS exemplifies the inescapable reality of closedness, where the crew should ever-present worry on the sustained operations of its ACE.

Following this line of thought, an ACE demonstrator demonstrates how human life must adapt in closed-system conditions, and allows a direct understanding of its impacts on the mini-biosphere in which it lives, more strikingly compared to larger scale biosphere. As highlighted by Walker et Granjou (2017), 'MELiSSA's project to construct a viable ecological 'niche' for human beings in the extremely abiotic and life-hostile conditions of outer space pulls into technological focus the obvious, but often forgotten fact that the minimum unit of life is not the individual organism or species, but the organism-within-its environment, as stated by Bateson (1973, p436). As described by Hendrickx & Mergeay (2007), the 'action of microbial consortia inhabiting interconnected bioreactors' can enable life support functions in CH for space travel and extreme environments on Earth[596], so that ACE can be considered as 'artificial

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[593] Cf §4.3.

[594] The more compact the CH becomes, the smaller buffer volume it offers.

[595] Cf §4.2.

[596] Hendrickx & Mergeay (2007, p. 231): 'Support of human life during long-distance exploratory space travel or in the creation of

setup of minimal life-support communities, inspired by minimal self-sustaining ecosystems' that generate measurable and exploitable data. The project to engineer such minimal biosphere capable of reliably sustaining human life thus implies a human/microbe association with the fewest possible species (Walker & Granjou 2017). With its immediate sealed environment for its occupants, a fully ACE-based CH, providing LSS to its inhabitants, is a nearly perfect example of domesticated habitat which could be considered as a minimal habitat unit.

For achieving the down-scaling process of initially immense ecosystem volumes with large buffers (including large-scale ACE such as Biosphere 2[597])[598] up to the minimal ACE volume to supply the needs of its inhabitants, a new set of technologies becomes necessary for sizing air regeneration, wastewater treatment and solid waste recycling systems. As mentioned above, space agencies like NASA provide and update baseline values (Anderson et al. 2018) useful for downsizing to the minimum the volumes in place in the CH while reaching self-sufficiency for extended periods.

A CH doted with an ACE can be perceived as a stepping stone to tackle and foster the transition towards a type III industrial ecosystem[599], that operates over long periods, under conditions where circularisation of matter makes resource and waste undifferentiated, while powered with solar energy.

Just as Graedel defined biological and industrial organism[600] elementary units of study in respectively biological and industrial ecology, CH gets materialised at the crossroad and intertwining of biological and industrial organisms. When considered as a minimal kind of industrial ecosystem[601], one could do an analogy between CH and an eco-industrial park (EIP)[602] of type 2 ('within a facility, firm, or organisation'), according to the taxonomy proposed by Chertow (2000) depending on the material exchange types in place. Ayres (2004) called EIP 'the next stage in the evolution of traditional manufacturing estates'. Accordingly, terrestrial habitat based on closed-loop systems taking place at the building scale could be considered as the next stage in the evolution of truly sustainable habitat. In light of this reasoning, the notion of CH could be further envisaged as an elementary unit for human living in self-sufficient habitat for relatively long periods of time, supplied with complete life support services provided by its embedded ACE. With its limited size compared to most buildings with several sub-habitats, a baseline CH should therefore become one of the key units of IE, offering the minimal habitat scale for the proper study of the relationship of human within limited surrounding ecosystem, happening at meso-scale of complexity level[603].

Another analogy that may come in mind when considering a CH as a minimal habitation unit is its comparison with a living cell. 'Cell' comes from Latin *cella*, 'small room, store room, hut' related to Latin celare 'to hide, conceal'[604]. In biology, the 'cell' corresponds to the constitutive element and the fundamental building block of an organized whole. It is built in a bottom-up way, as in the synthesis of macromolecules from elementary bricks, the micromolecules. This mode of functioning is found in hierarchical organisation at higher scales, as in tissue biology, physiology or ecosystem functioning. In

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human habitats in extreme environments can be accomplished using the action of microbial consortia inhabiting interconnected bioreactors, designed for the purpose of reconversion of solid, liquid and gaseous wastes produced by the human crew or by one of the compartments of the bioregenerative loop, into nutritional biomass, oxygen and potable water. The microorganisms responsible for bioregenerative life support are part of Earth's own geomicrobial reconversion cycle. Depending on the resources and conditions available, minimal life support systems can be assembled using appropriately selected microorganisms that possess metabolic routes for each specific purpose in the transformation cycle.'

[597] MELiSSA Pilot Plant, Biosphere 2, and other several past and current biosphere-related initiatives are listed in Annex C2a-§8.3 as they feature one or several component(s) that can be considered as part of a space or terrestrial LSS.

[598] Cf §4.2.1.

[599] Cf §3.8.1.

[600] Cf §2.2.2.2.

[601] Cf §4.3.

[602] Cf §3.1.

[603] Cf §3.1.

[604] 'Cell'. Online Etymology Dictionary: https://www.etymonline.com/word/cell (last retrieved on 10.03.2019).

particular, a eucaryotic cell – that is, a cell doted with a nucleus, such a human ones – represents a structure that can be considered both as a system and as a unit: first, as a complex system, as a cell combines organelles with specific metabolic functions (e.g. mitochondrion for energy production and biological respiration, endoplasmic reticulum for protein and lipid synthesis, Golgi apparatus for protein secretion or lysosome for molecular waste material and cellular debris processing); and second, as a unit, as eucaryotic cells are the smallest structural and functional unit of life classified as a living thing, from which all living multicellular organisms are composed. Thus, the 'living cell' can be considered as the functional basic unit of life. 'Life' is characterised typically by the following criteria (the correspondence with the proposed key concepts for ACE analysis in the perspective of IE[605] is mentioned): 1) order[606], 2) reproduction[607], 3) growth and development[608], 4) energy use[609], 5) response to environmental factors[610], 6) homoeostasis[611], 7) evolution and adaptation[612].

The ecosystem being one of the principal units of study for communities in ecology[613], the notion of 'habitat' is another more specific to the level of species themselves. In an ecological context, a habitat defines an environmental area that is inhabited by a particular species. It is the natural environment in which an organism lives, or the physical environment that surrounds, influences and is utilised by a species population. In biology, the term 'habitat' originally appeared in the 18th century in Latin texts on English flora and fauna to define an area or region where a plant or animal naturally grows or lives. Literally 'it inhabits' comes third person singular present indicative of habitare 'to live, inhabit, dwell'[614]. Thereby, etymologically speaking, the analogy between the terms 'cell' and 'habitat' can be acknowledged.

Table 11 shows the analogy between a living cell and a self-sufficient habitat as a particular case of CH.

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[605] Cf §3.

[606] Cf §3.2.

[607] Cf §3.7.

[608] Cf §3.2.

[609] Cf §2.2.2.4.

[610] Cf §3.6.

[611] Cf §3.8.3.

[612] Cf §3.8.

[613] Cf §2.1.

[614] 'Habitat'. Online Etymology Dictionary: https://www.etymonline.com/word/habitat#etymonline_v_1356 (last retrieved on 10.03.2019).

Biosphere (a living cell)	Technosphere (a self-sufficient habitat)
Cell wall / cell membrane.	Habitat external walls.
Cell membrane.	Almost only flow crossing over during closure campaign/mission is information, with the exception of potential leakages.
Smooth & rough endoplasmic reticulum.	Greenhouses for macromolecules synthesis.
Golgi bodies.	Food processing.
Lysosomes.	Waste treatment units.
Mitochondria.	Batteries.
Chloroplasts.	Solar panels and photobioreactors.
Ribosomes.	3D printers.
Cytoskeleton.	Pipes and electrical wires.
Cytoplasm.	Corridors.
Protoplasm.	Atmosphere.
Vacuole.	Greywater tank.
Micro and macromolecules such as carbohydrates, triglycerides and proteins.	Nutriments/food and inhabitants.
Nuclear envelope.	Maintenance room wall and door with restricted access (e.g. biometric).
Nucleus.	Technical maintenance room.
Nucleolus.	Copy machine / Germination unit.
DNA.	Original blueprints of the process-flow diagram.
RNA.	Copies of blueprints.
Gene.	Process, unit operation (as technical DNA).
Genetic repair kit.	Repair mechanisms from health and safety countermeasures. Backup systems.

Table 11: Biosphere vs technosphere.
Living cell and self-sufficient habitat analogy. Just as cells can form cellular tissues in the biosphere, self-sufficient habitat can be combined to form a urban tissue such as a small city cluster.

Just as the cell is the basic functional unit of life, it is proposed here that an autonomous and self-sufficient habitat such as a CH for what concerns the cycling of material flows, should be envisioned as a relevant basic unit for a dwelling place, a minimal habitation unit typically sized for 2 (SP1 and SLP1), 3 (BIOS) or up to 6 inhabitants (FIPES, Mars500, Biosphere 2).

In conclusion, by reconditioning to human purposes a limited set of simplified ecosystems processes and services within a liveable habitat, CH have the capacity to ensure self-sufficiency for one or few occupants. A CH can be considered as a minimal habitat, a living unit for long-duration dwelling within a sustainable habitat, a man-made closed ecosystem for humans.

13.5 Final considerations

At this stage, a reflection on the technological trajectories in the framework of ACE development seems necessary, in order to approach the ways these technologies are disseminated and used.

Technology enablement uses technical solutions and tools to produce an outcome. It can describe the technical maturity of a technology and applies well to the development of space ALSS technology. Technology leverage refers to Ray Kurzweil assertion that technologies can develop at an exponential scale[615]. In the context of ACE development, technology leverage is the ability to create increasing value despite the limited amount of resources available and leads to acceleration of change and expansion of innovation. The broader notion of technology empowerment means that innovation is increasingly accessible to ordinary people of limited means (Warren et al. 2017) and encompasses the spreading and use of technological solutions by a wider audience. In a nutshell, technology empowerment combines technology enablement (the use of technology) and technology leveraging (bringing together the framework conditions for adopting a technology at a faster rate).

ACE-based technology empowerment foster waves of technologies that are transformational at two levels: first for the technology transfer and spin out from space to Earth-based applications, second to the diffusion and appropriation of those applications by a broad panel of users.

A CH demonstrator represents an experimental platform for exploring how we could live tomorrow in a perennial way. Its individual components or combination of them can offer self-sufficiency features in several terrestrial contexts. The products (i.e. low water aeroponic food production, CO_2 capture or biomonitoring through miniaturised sensors) are not necessarily connected to the achievement of complete loop closure or to long residence time within the habitat. As discussed in the previous sections, at the level of sealed habitation systems, the internal habitable volume and mass efficiency remain one of the top-level operational objectives.

Based on the conceptualisation and further operationalisation of minimal habitats discussed above[616], numerous terrestrial applications can be developed at different scales of urban habitat, with ACE subsystems and components at their core. For instance, ACE-related solutions for material flow circularisation optimise the performance at the building scale. Apart organic waste valorisation and resource recovery combined to on-site food production, this includes measurement of exposures (including food, drugs, micropollutants, etc.) and analysis of their effects on the health and on the environment, e.g. indoor air quality control (biological and chemical risks), at-home health monitoring and remote assistance, maintaining of the quality of life and well-being of habitat occupants. Section §14.2 maps Earth-based applications of ACE and their possible contexts of use.

An ACE demonstrator draws attention to the fact that on both Earth and Mars, it is all about taking our behaviours into account and fostering the healthiest possible immediate environment.

The approach for CH also paves the way to a more sober view of the limits of technological development and an understanding of what we all intuitively know about life: how we live, the quality of our relationships, the food we eat, how we use our bodies and the environment in which we bathe determines us far more than technologies ever will.

In a CH and especially in a space habitat everything is under extreme constraints (as compared to terrestrial context): not just resource, but also space and even people[617]. Therefore, it seems relevant

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[615] Dan Woods, Technology Leverage, posted in Early Adopter Research: https://earlyadopter.com/2018/03/09/technology-leverage (last retrieved on 10.05.2020).

[616] Cf §13.1 to §13.4.

[617] Häuplik-Meusburger & Bishop 2021, p.185: 'One unbendable fact about the logistics of space travel and habitation therein is that everything is limited; physical space, storage, air, water, food, power, fuel, medicine... everything, even people. Once established, possibilities to set up in-situ or remote mining and resource acquisition will be explored. But until that capability is in

to explore how space exploration allow us to better understand life in confinement.

In conclusion, as constraints and challenges on Earth keep growing, ACE development presents a strong potential for the technological empowerment of self-sufficient and self-standing habitats on Earth by leveraging the acceleration of eco-innovation processes[618] related to material loop closure. In return, this technological empowerment from ACE development clearly contributes to the operationalisation of IE.

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place and the inventory of accessible resources identified, we must plan to make do with what we pack and bring. Such finite resources mean building to thrive just got a lot harder.'

[618] Cf §14.4.

14 Contributions of ACE development to terrestrial sustainability (RO3.2)

Traditionnally, the concept of (terrestrial) sustainability is usually defined by combining the environmental, economic and social components of sustainable development. The later three pillars of sustainable development are also coined 'triple bottom line' or 'planet, profit and people'[619]. This chapter highlights the contributions of ACE development to terrestrial sustainability (RO3.2), which flow from the ground preparation of manned planetary exploration mission and parallel development of specific ACE-based terrestrial solutions. It first summarises the contributions to terrestrial sustainability identified previously (§14.1). Next, it analyses the potential of ACE development for Earth-based applications (§14.2). It then introduces the notion of circular economy (§14.3) and presents a selection of contributions of ACE development to circular economy (§14.4). Eventually, it provides considerations on the contributions of ACE development to terrestrial sustainability (§14.5).

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[619] Jeroen Kraaijenbrink. 'What The 3Ps Of The Triple Bottom Line Really Mean', published on Forbes online magazine: https://www.forbes.com/sites/jeroenkraaijenbrink/2019/12/10/what-the-3ps-of-the-triple-bottom-line-really-mean/?sh=40d95b735143 (last retrieved on 16.10.2021).

14.1 Contributions of ACE development to terrestrial sustainability identified previously

Gradually, this thesis showed evidence that ACE development can be envisaged independently of the space ALSS[620], given its intrinsic relevance for the research on natural and industrial ecosystems of which ACE represent an extremely simplified version.

Initial considerations from the previous chapters of this work exemplified some of the ways ACE development contributes to terrestrial sustainability.

✧ *Considerations from Part I:*

In the first part of this dissertation, one of the crucial questions was to determine how the R&D on ACE can help better emulate the natural principles and processes and consequently help promoting a more effective 'maturation' of industrial ecosystems[621], and reversely what can scientific and industrial ecology tell us about the design and management of ACE. By implementing IE in constrained conditions, the contributions of ACE development have the capacity to enrich its conceptual foundations, as per §3 on the key concepts for ACE analysis in the perspective of IE, or through the use of ACE for refining the analytic tools and methodologies of IE like MFA[622] or LCA[623]. In this respect, this PhD work explored areas of interest where ACE can clearly contribute to put IE concepts into action and leverage its operationalisation in both a singular and measurable way.

A fully cyclic space ACE would correspond to a type III ecosystem, in which resources and wastes become indistinguishable, as each waste flow would represent a resource for another part of the system. In such engineered ecosystem, cyclicity would be completely achieved (except for energy flows which are inevitably dissipated), making the system ultimately sustainable[624]. This resource circularisation capacity is one of the reasons why space ACE have been considered as a model for industrial ecosystems under extreme constraints[625]. Therefore, ACE development represents a highly relevant model for advancing thinking and practices in IE, in the perspective of terrestrial sustainability.

✧ *Considerations from Part II:*

The in-depth study of ACE and CH within the framework of the Oïkosmos programme seems all the more relevant for terrestrial researchers[626], with two of its four fields of investigations, namely IE[627] and closed and sustainable habitat[628], clearly connected to terrestrial sustainability.

Furthermore, an ACE simulator enables the interweaving of skills and technologies necessary for the development and analysis of closed systems[629]. The scope of the Oïkosmos programme profiles the ACE demonstrator not only as a useful tool for exploring specific aspects of industrial and natural ecosystems, but also as an experimental facility for mastering the constraints of an almost perfectly CH.

In addition, a ground-based testbed vastly based on space-compatible ALSS-related technologies is a useful analogue facility to study and implement terrestrial sustainability, with environmental issues in its

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[620] Cf §6.1.2,.
[621] Cf §3.8
[622] Cf Annex A-§7.2.3.
[623] Cf Annex A-§7.2.5.
[624] Cf §3.8.1.
[625] Cf §4.3.
[626] Cf §5.
[627] Cf §5.3.
[628] Cf §5.6.
[629] Cf §6.

heart[630]. In particular, the research in such an experimental platform is useful to explore the concept of 'systemic sustainability'[631].

Moreover, the scope of BELiSSIMA Phase A spin-out project described in §8 focuses on water recycling and micropollutant behaviour in the perspective of terrestrial sustainability.

Then, the roadmap of SUMIT Innosuisse project[632] takes places within the circular sanitation economy, as further described later in this chapter[633].

Finally, the ESA Closed Habitat Forum 2016[634] addressed the contributions of CH to sustainable resource management and sustainable habitat, to raise the level of awareness around them and make them economically attractive, notably to private stakeholders.

✧ *Considerations from Part III:*

As mentioned earlier[635], the vision of ESTEE is to facilitate sustainable living in both Earth-based and space ALSS within CH. SP1 and SLP1, ESTEE's proofs of concept under development[636], notably aim to enhance the development of Earth-based applications from space ALSS, and especially technological solutions impacting positively terrestrial sustainability (inedible biomass valorisation, nutrient recovery, biosensing of health and environmental biomarkers, down-scaled waste treatment and food production units, etc.).

Subsequently, the question of the habitability optimisation of CH in the perspective of sustainable habitat was addressed[637]. Also, the implementation of an ESA project based on the review and combination of existing referentials for sustainable construction and for ALSS related fields was also envisaged[638].

Afterwards, CH was conceptualised as a minimal habitat for self-sufficiency in the perspective of IE[639]. Particularly, terrestrial habitat based on closed-loop systems taking place at the building scale was considered as the next stage in the evolution of a truly sustainable habitat.

Later, the technology empowerment from ACE development for self-sufficient habitat on Earth was discussed[640]. A CH demonstrator was considered as an experimental platform for exploring how will we dwell in tomorrow in a more sustainable way. Apart organic waste valorisation and resource recovery combined to on-site food production, this includes measurement of exposures (including food, drugs, micropollutants, etc.) and analysis of their effects on the health and on the environment, e.g. indoor air quality control (biological and chemical risks), at-home health monitoring and remote assistance, maintenance of the quality of life and well-being of habitat occupants. In this context, ACE-related solutions for material flow circularisation can optimise of the performance at the building scale, and CH (sub)systems are capable to support society with more environmentally oriented solutions.

The next section examines the potential of ACE development for Earth-based applications.

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[630] Cf §5 and §6.
[631] Cf §6.1.3.
[632] Cf §9.3.
[633] Cf §14.4.
[634] Cf §10.1.
[635] Cf §13.1.
[636] Cf 13.2.
[637] Cf §13.3.
[638] Cf Annex H.
[639] Cf §13.4.
[640] Cf §13.5.

14.2 Mapping of Earth-based applications of ACE

This section analyses the potential of ACE development for Earth-based applications. It starts by mapping their related possible market segments based on Oïkosmos Report and on market research and stakeholders analysis (§14.2.1). Then, it introduces the assessment of space ALSS technologies business and financial potential for Earth-based applications, based on ESA Express Procurement [Plus] – [EXPRO+] study, in which ESTEE led the technical side of the assessment (short project description in §14.2.2).

14.2.1 Terrestrial applications in relation to the study of ACE[641]

In general, Earth-based applications of closed-loop systems are geared to operate in a decentralised way in contexts with significant and growing constraints as discussed previously[642]. The similarities between space and terrestrial habitats will continue to increase, bearing in mind that they can already be acknowledged in certain terrestrial sites evolving in extreme conditions, such as in ecosystems suffering from resources shortage (water, phosphorus, etc.), dissipation and/or pollution (contaminated resources), in remote regions, as well as in confined and isolated habitats (islands, mountains ecosystems, polar bases in the Arctic and Antarctic, large ships, submarines, bunkers, etc.), and also in built-up ecosystems (city infrastructures, residential and industrial areas, hospitals, places hosting large events, hotels and resorts, etc.). In most contexts of use on Earth, there is a need for decentralised small-scale recycling units, – often with food production – and sometimes monitoring – capacities as shown in Table 12, just like what would be needed on the Martian surface with a MELiSSA-type system.

Historically, the space sciences and technology R&D had a significant driving effect on other research domains and on the economy through Earth-based applications. The case for decentralised wastewater systems[643] is a good example of the relevance and potential of space ACE technologies for terrestrial ecosanitation solutions. Indeed, cities and LSS for space missions somehow share similar challenges and ambitions. Water is the largest of all urban and household flows when measured as weight and volume (Voskamp et al. 2017), and this is also the main consumable to be regenerated in a space habitat[644]. Acknowledging this background, Adams et al. (2004) explored the synergies for the technological spin-out from space sanitation to terrestrial sanitation and vice versa. In particular, decentralised wastewater treatment systems and source separation sanitation gained a lot of attention due to the wide implementation potential of water decentralised systems worldwide (including in developing countries) (Larsen et al. 2013). Technologies for source separation encompass solid waste treatment, biological nitrogen conversion processes, electrochemical systems and membrane processes, to cite just a few. Despite their challenges in terms of hygiene, user acceptance, implementation in existing infrastructure, as well as for the use of the recycled nutrients for agriculture, decentralised and source-separating systems have the capacity to achieve food security through phosphorus recovery, as well as to deal with the issue of micropollutants in urban water management (Larsen et al. 2013).

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[641] Related research outputs:

- Terrestrial applications in relation to the study of ACEs is discussed in the final considerations of the Part II of the Oïkosmos Report (Annex A-§11.3).
- For a review of Biospheres see Annex C2a-§8.3 of BELiSSIMA Phase A TN118.1.4.

[642] Cf §6.1.2, Annex A-§6.1.4 and §13.4.

[643] Cf Annex A-§7.3.

[644] Cf §4.2.2.

	(a) R&D	(b) ACE-BASED TERRESTRIAL APPLICATIONS & SERVICES						(c) SPACE APPLICATIONS
	Tech transfer Research synergies	City Infrastructure	Residential areas	Commercial / Industry area	Places hosting large events	Challenging climates, remote and/or isolated areas (*)	Defence	Flight
Researching and experimenting	ACE/CH demonstrators. [MELiSSA, ESTEE, Liquifer, Enginsoft, Biosphere 2]	-	-	BELISSIMA project	-	Concordia station, EDEN-ISS, SHEE [Firmus, Liquifer]	-	ISS, shuttle, Moon/planetary base. [SpaceX, Sener, Qinetiq, Thales Alenia Space, RUAG Space, AeroSekur, Paragon Space Development Corporation, Sherpa engineering, Enginsoft, space agencies]
Exploring and discovering	-	-	-	-	-		-	
Surviving	-	Post-disaster bunkers and nuclear shelter. [Eco Modular Buildings, SotradWater]		-	-	Post-disaster bunkers, nuclear shelter, refugees camps, emergency solution for water, decentralized wastewater treatment systems (incl. nutrient recovery and micro-pollutant removal), food production systems, oil rig, boats, submarine, underwater working station, etc. [FGWRS, Vuna, SEMiLLA Sanitation, Anywhere Zest, Ecosec, The Sustainable City/Masdar, Nautisan]	Bunkers and nuclear shelter, survival kits for field operations, decentralized wastewater treatment systems (incl. nutrient recovery and micro-pollutant removal), food production systems.	
Working / Living	-	Decentralized wastewater treatment systems (incl. nutrient recovery and micro-pollutant removal), biofacade, living wall, sensors for smart monitoring. [Veolia (Biostyr), MADEP, Xenometrics, SkyGreens, Vuna, Anywhere ZEST, Ecosec, Biopolus, SUMIT]	Decentralized wastewater treatment systems (incl. nutrient recovery and micro-pollutant removal), tiny house, biofacade, living wall, sensors for smart monitoring. [FGWRS, SUMIT, Anywhere ZEST, Ecosec, Vuna Earthships, XTU Architects, Biotecture, Algosource, SUMIT]	Decentralized wastewater treatment systems (incl. nutrient recovery and micro-pollutant removal), biofacade, living wall, food production systems (plants, food supplements, algae nutrients), sensors for smart monitoring. [Veolia (Biostyr), MADEP, Xenometrics, SkyGreens, Vuna, FGWRS, Anywhere ZEST, Ecosec, Vuna, Earthships, XTU Architects, Biotecture, Biopolus, Algosource, Biotecture, Combagroup, Aerofarms]	-			-
Experiencing in real life / in virtual reality	-	Performer place, museums, self-sufficient hotel / Virtual visit. [Anywhere ZEST, Ecocapsule]	-	-	Decentralized wastewater treatment systems (nutrient recovery from yellow and grey water in festival or sport event toilets/showers), self-sufficient hotel. [Roland Garros (FGWRS), VUNA, SEMiLLA Sanitation, Ecosec, Anywhere Zest, EcoCapsule, Kompotoi, ToiToi]	Extreme location tourism, with systems for self-sufficiency (moutain hut, boat trip, self-sufficient or underwater hotel, outstanding journeys).	-	-

Table 12: Contexts of use of ACE-based solutions.
Contexts of use are distributed between R&D activities (a), ACE-based terrestrial applications (b), ACE-base space applications. (*) e.g. warm/cold temperature, snowfalls, underwater. Source: Adapted from ESTEE.

In addition to yellow and black water, source separation of wastewater has been applied in many eco-housing projects, where grey water as well as kitchen waste are collected and transported in separate pipes (Zeeman et al. 2008). Source separation is claimed to result in a number of benefits that enhance water use efficiency and resource recovery from effluents (Kujawa-Roeleveld & Zeeman 2006). CH and ACE environments are excellent case studies to further develop robust decentralised sanitation systems, as the separation of the flows excreted by humans is of primary importance. Whether applied in a space or terrestrial context, source separation and decentralisation present strong commonalities. Therefore, the clear convergence of their technological pathways exemplifies well the synergy spirit and cross-fertilisation potential of ALSS related technologies. Circular sanitation economy will be further discussed later in the chapter[645].

In the context of CH, and as exemplified earlier[646], biospheres are types of ACE operating relatively independently, without being influenced by on-site external conditions, and with very little - if any - interactions with the neighbouring natural ecosystems in terms of material flow exchanges. Earthships are examples of off-grid eco-habitat that are claimed to only local, low-tech or waste materials for its construction.

As highlighted by Hendrickx & Mergeay (2007), 'engineered closed-loop systems can also function as commercially exploitable tools or as model microbial ecosystems to develop and improve recycling technology, to study and compare population composition and genetic evolution of self-supporting and disturbed ecosystems, or to study the effects of the presence or absence of certain compounds in the main transformation cycles.'

Sherpa Engineering, one of the historical MELiSSA partners expert in control-command modeling (Brunet 2020), modelled the extremely complex closed-loops system in an iterative way. In addition to its space interest, its elaborated methodology enabled the formulation of a software solution suite (Sherpa Engineering 2020) that has applications in various sectors (automotive industry, smart buildings, etc.) that can benefit from circular system know-how.

Also, CH are examples of infrastructures for self-sufficiency that can be used as refuges for surviving in sites hit by natural disasters or conflicts or in the wake of global catastrophes such as human pandemics, supervolcano eruption, asteroid impact, nuclear warfare, nanotechnology and artificial intelligence accident (Baum et al. 2015).

CH offer living opportunities and are relevant in constrained terrestrial areas, in mountainous, desertic or arctic regions, underwater or underground locations (including bunkers) in terms of safety, R&D capacities, tourism, real estate. In particular, underground environment, such as tunnels are appropriate analogue environment. For instance, Asclepios mission (Annex F4), took place in the Grimsel dam maintenance tunnel, in Switerland's Alps). Also, a Swiss initiative committee founded the internationally pioneering Swiss Center of Applied Underground Technologies (SCAUT) (2018), with notably the project 'Underground Green Farming' based on aeroponics (SCAUT 2019).

In 2017, ESTEE was awarded for the implementation of an INTERREG project, with the participation of UNIL and the agricultural institute of Grangeneuve for developing a smart connected, modular and autonomous greenhouse, through the SCIMA project (Serre Connectée, Intelligente, Modulaire, Autonome)[647], and thus connecting wastewater recycling with fresh food production in a decentralised way on a small scale. The system was aimed to increase the biocapacity of constraining environments in terms of resources generation (fresh food) and absorption of what comes from consumption (waste valorisation, while limiting the environmental footprint as much as possible. The initial targeted areas

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[645] CF §14.4.4.

[646] Cf Annex C2a-§8.3.

[647] Cf short project description in Annex I.

application were urban or mountainous (typical of the cross-border INTERREG region). Initially funded with a budget of CHF 928'000.-, the project had unfortunately to be stopped after mid-project completion, due to the withdrawal of the French leader (Groupe Brunet) for lack of available human and financial resources to achieve the prototype implementation[648].

As stated in Oïkosmos Report [649], the triple evolution of IE[650], of the omic sciences[651] and of the new ICT [652] position ACE at the interface of various technological dynamics. Combining, linking and integrating them make it possible to envisage new applications, or even real paradigm shifts – some of which have already been achieved or are underway –, in particular for maintaining health or improving environmental performance.

ALSS related technological dynamics show some of the possible ways towards an artificialisation of nature, that could be used to implement IE operational strategy towards sustainability. But as Erkman pointed out (Erkman 2004), it is not enough to consider these technological trajectories in isolation, separately by extrapolating the potential of each, as if things could remain unchanged elsewhere. It is rather crucial to consider the possible effects of their convergence. For instance, and applied to ACE, it would consist in reprogramming a bacteria to maximise the waste conversion yield of an ACE microbial reactor, downsizing waste treatment unit at the habitat scale, food production systems that make the habitat fully self-sufficient.

In addition, the IE approach allows to deal with the challenges of recycling with a broader vision than those offered by simple 'cleantech' or specific ecotechnologies, and to envisage the integration into ACE of the so-called disruptive, critical or pivotal technologies, which could develop from one or more of the following technologies: the recovery technologies on an 'industrial' scale through chemical and biochemical valorisation of CO_2[653] and biorefinery[654]; (new) ICT, such as: embedded technologies, with the development of intelligent, connected, autonomous and ultra-efficient sensors[655]; and ubiquitous (mobile) computing, with the development of mobile telehealth applications (Annex A-§9.4), including smart health biomonitoring devices as developed in SUMIT project roadmap[656]; and advanced materials, with superior and high-performance characteristics, properties and functionalities, including those produced by nanotechnology or biotechnology processes[657].

Following this logic, spurring initiatives such as X-Prize are increasingly used to accelerate the R&D on space technologies, as well as for tacking global issues on Earth [658]. In a potential attempt to counterbalance the negative impacts of its space endeavour, Elon Musk and the Musk Foundation announced in 2021 a M$ 100 competition on atmospheric carbon removal[659].

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[648] For context and partners profiles, project description, workpackages and deliverables, see:

- Annex I1: Fiche pré-projet 2014-2020 Programme Interreg V France-Suisse du 04.04.2017;
- Annex I2: Convention d'utilisation des aides au titre du Programme Interreg V France-Suisse 2014-2020 du 10.01.2018;
- Annex I3: Example of intermediary deliverables: WP B3 - Projet SCIMA : Rapport de définition du système substrat et irrigation.

[649] Cf Annex A-§11.3.

[650] Cf Annex A-§6.2 and Annex A-§7.

[651] Cf Annex A-§6.3 and Annex A-§8.

[652] Cf Annex A-§6.4 and Annex A-§9.

[653] Cf Annex A-§7.4.3.

[654] Cf Annex A-§7.4.4.

[655] Cf Annex A-§9.3.

[656] Cf §9, §14.4.4.

[657] Cf Annex A-§10.6.

[658] Toivonen (2020b, §7): 'The actively growing space tourism industry has three major operators with private and influential funding: Virgin Galactic, SpaceX and Blue Origin, competing for the status of pioneers of human space flights, and all originally benefiting from governmental initiatives such as NASA's Space Launch and the XPRIZE competition to prepare the technology for a reusable launch vehicle.'

[659] Overview of the incentive prize, one of the largest in history: https://www.xprize.org/prizes/elonmusk (last retrieved on 12.10.2021). As stated in the X-prize website: 'To win the grand prize, teams must demonstrate a working solution at a scale of

All of these ‘enabling technologies’ encompass new processes, new techniques or new materials that offer functionalities not available today, allowing the development of new applications. Oïkosmos programme could have a great card to play in such development. With such an ACE simulator project, ESA would have the opportunity to develop and deploy a particularly broad research programme. This major project would necessarily give a major role to recycling in each of the life support components. But, as suggested in the Oïkosmos Report , it would go far beyond the engineering aspects of ACE. Relevantly, the research agenda incorporate and encompass topics related to ALSS, with themes such as systems biology, personalised nutrition, telehealth, psychosociology, etc. While all these subjects, disciplines and other technologies have made remarkable progress in recent decades, their interaction in a closed environment has not received the necessary attention. This is partly due to the lack of a significant experimental site with both the right characteristics and environment, while operating on a sound scientific basis.

In parallel, research synergies also allow the establishment of numerous collaborations with non-space institutions. By promoting the technology transfer from academic research on closed systems to industry, the Oïkosmos programme promises many direct terrestrial spin-offs based on innovative applications that the European citizen should benefit from. With the broad scope of its research agenda, the ACE demonstrator leads us to predict the development of efficient and useful tools, technologies and solutions to improve living conditions in CH and confined environments, with fields of application as varied as recycling and recovery of organic waste, environmental monitoring, biomonitoring of physiological parameters, biorefinery, production of functional foods, etc.

While introducing SP1[660], it was envisaged that compared to space agency ground simulator for space ALSS (ie. FIPES), a CH demonstrator such as SP1, that is driven by a private initiative, may be more easily connected to the implementation of the synergistic R&D Oïkosmos programme and thereby may present a more direct relationship to the development and commercialisation of terrestrial solutions.

As a reminder[661], the combination of technologies to be integrated in SP1 aspires to face some of the major challenges for a future expansion of Earth-based applications ALSS, such as:

- technology development for waste valorisation, such as for removal, retention or degradation of inedible biomass;
- increased nutrient separation/recovery technology[662];
- investigation of microcompounds and trace elements behaviour in closed systems[663];
- sensors for accurate health and environmental biomarkers measurements and near real-time monitoring[664];
- down-scaling to small waste(water) treatment and food production units and applications to closed and confined systems[665].

At this stage and in order to give an overview, Figure 50 summarises the main areas of applications discussed in the Part II of the Oïkosmos Report for the fields of IE, systems biology, ICT and closed and

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at least 1’000 tonnes removed per year; model their costs at a scale of 1 million tonnes per year; and show a pathway to achieving a scale of gigatonnes per year in future. Any carbon negative solution is eligible: nature-based, direct air capture, oceans, mineralization, or anything else that achieves net negative emissions, sequesters CO_2 durably, and show a sustainable path to achieving low cost at gigatonne scale.’

[660] Cf §13.2.

[661] Cf §13.2.2.

[662] Cf Figure 36 and Annex A-§7.4.2 on MASSTER proposal.

[663] Cf §8 on BELiSSIMA project.

[664] Cf §9 on SUMIT projects.

[665] Cf Annex I on SCIMA project.

sustainable habitat.

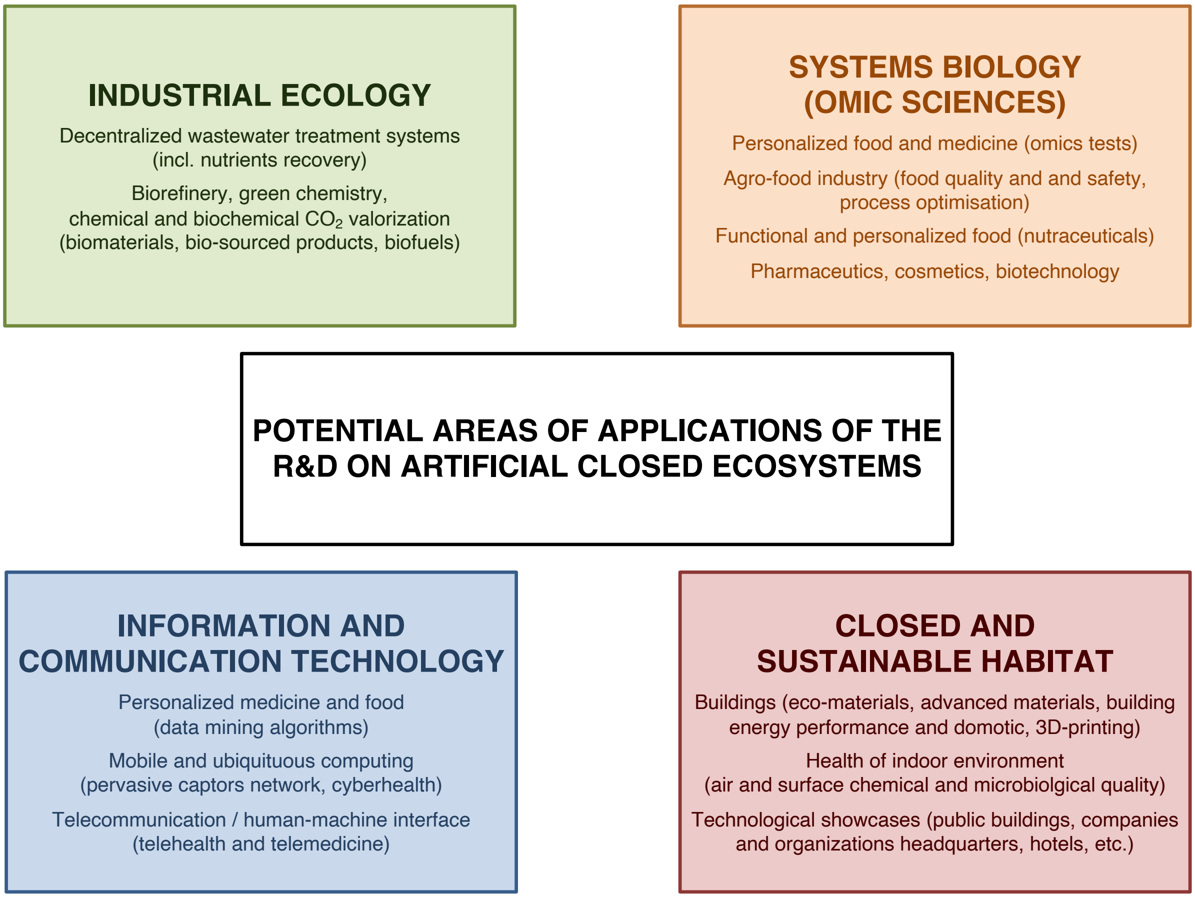

Figure 50: Main areas of application of ACE.
Main areas of application that could emerge from synergistic research on ACE and their context of use within Oïkosmos programme. Source: Théodore Besson, 2016.

In more details, these areas of application encompass the following topics:

Industrial ecology

✧ Decentralised wastewater treatment systems (physico-chemical and bacterial). Highly efficient recycling systems for organic waste (better yield, decomposition and productivity) coupled with fertiliser production by recovering nutrients from urine, ultrafiltration and nitrification systems, (industrial) treatment of grey water or slurry, separating toilets. Use of cyanobacteria for the treatment of yellow and grey water. Context of use / place of application: urban infrastructure, residential areas, industrial areas, large cultural and sports events, hotel complexes; isolated habitats: island habitats, mountain huts, (ant)arctic bases, ships, bunkers; equipment for interventions in case of natural disasters.

✧ Biorefinery / green chemistry / chemical and biochemical CO2 recovery. Biomaterials: biopolymers; plant fibres and biosolids used as bricks and construction materials (buildings, roads), biodegradable plastics. New degradation pathways for plant fibres. Use of cyanobacteria for air regeneration. Bio-sourced products: new building blocks and intermediary for the synthesis of chemical products (solvents, lubricants, pastes, etc.) for industry (cosmetics, pharmaceuticals, plastics, metallurgy, etc.). Third generation biofuels from microalgae.

Systems biology

✧ Personalised medicine: fast and cheap ‘omics’ tests for analysis of genomic (PCR technologies), metabolomic or nutrigenomic composition of biological samples (urine, blood, feces, sweat, saliva), including surveillance of key biomarkers, with a view to improving diagnoses (disease detection) and medical prognoses (preventive treatment); highly sensitive detection systems (toxic metabolites, hormones, drugs, microbes, viruses, prions, etc.) via sensors measuring physiological data.

✧ Functional and personalised nutrition: dietary supplements (including cyanobacteria), nutrigenomic nutrition (alicaments, nutraceuticals, functional nutrients), fortified foods, biofortifiers (including animal husbandry and agricultural crops). Toxicity testing (microbiological monitoring of nutrients based on genotyping of micro-organisms). Development of single-cell proteins with bioactive properties (e.g. anti-cholesterol).

✧ Food industry. Food quality and safety: industrial processing, quality control (microbiological quality assessment tests of food via omics technology, e.g. for DNA and protein detection and characterisation), improved consumer labelling. Industrial biology processes improving the efficiency of (photo)bioreactors; agroindustrial cultivation processes optimising the productivity of plant growth chambers. Super-efficient food production systems: automated, miniaturised greenhouses optimising volume (vertical farms) and/or operating in closed systems under highly constrained conditions (temperature, volume, etc.), based on hydroponics, aeroponics, aquaponics. Soil enrichment (fertilisation with co-products). Local micro-algae production systems. Food based on microalgae, synthetic meat or insects. Beverage production: biosensors monitoring immobilised biomass (sparkling wine industry). Lighting systems for (photo)bioreactors (3D lighting) based on optic fibre networks.

✧ Pharmaceuticals, cosmetics, biotechnology. New protocols for testing the effects of bioactive molecules (alicament, drug, probiotic, pollutant) on ecosystems or on the human metabolome or nutrigenome. Fight against malnutrition based on micro-organisms. Rapid air and surface monitoring to ensure the safety of pharmaceutical products (vaccines).

Information and communication technology

✧ Personalised medicine and food: algorithms for data mining of environmental and health data.

✧ Mobile and ubiquitous computing. Distributed sensor network measuring environmental data in a decentralised way: microsystems for early detection of pollutants in air and water (traceability of undesirable chemical and biological compounds, bioindicators); Embedded technologies: facial and movement recognition systems (sensing of behaviour and social interactions). Software for personalised recommendations according to user profiles (allergies, asthma), according to the location and analysis of omic signatures, etc. (cyberhealth). Intelligent clothing and textiles: performance medicine, sports environments (fitness, training), orthopaedic rehabilitation engineering, remote medico-social care, ‘wearable computing’ applied to physical rehabilitation, high-level sport, risky professions.

✧ Telecommunication/human-machine interface. New telehealth and telemedicine procedures and interfaces: teleconsultation, remote monitoring, remote medical assistance (telecare, medical robotics), as well as biomedical tele-training. Human-computer interfaces (augmented reality, telepresence, entertainment industry); mobile and connected health (mHealth).

Closed and sustainable habitat

✧ Construction. Ecomaterials, advanced materials (membranes for inflatable structure). Architecture and materials improving the energy performance of the building and its facilities; building monitoring devices, measurement of hygrothermal changes in a controlled environment (insulation tests, remote equipment inspection); artificial and natural lighting systems, ambient light detector (colour sensing); home automation devices (based on gestures, eye movement, etc.), maintaining the quality of life and well-being of residents (such as elder people, e.g. fall detector). 3D printing: new techniques for 3D printing of structural components of buildings, or entire buildings, with robotic assistance or in a partially automated manner. Ergonomic equipment to optimise comfort and habitability. Photovoltaic panels adapted to hostile environments (deserts, solar islands, avalanche barriers, etc.).

✧ Indoor environmental health. Indoor air purification and surface (bio)contamination detection systems (hospital hygiene, quality control in pharmaceutical industry), clean room sterilisation (immunodeficient patient care), antibacterial blankets.

✧ Technological showcases (closed habitats): public buildings, company or organisation headquarters, etc.

In short, Earth-based applications of ACE have shown so far a wide range of sectors as different as biotechnologies, life science, agrifood, and wastewater treatment, etc. Reversely, the application of ACE in a terrestrial context accumulates experience for future space exploration missions. The above list shows that commercialisable Earth-based applications based on spillovers from space ACE are countless, and that they target in priority the improvement of citizens health and quality of life, as well as of the protection of environment. In addition, ACE development itself is perceived as a necessity by some investors[666].

In any case, the ACEs will have many surprises in store to enhance the operationalisation of terrestrial sustainability in the perspective of IE.

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[666] As envisaged in a personal communication with Omar A. Fayed, founder of ESTEE, who sees that ‘a solid necessity will drive ACE development initiative, and not the luxury perspective.’, striving for uniqueness and advancedness, he claims that ‘a terrestrial market has to be formed around ACE pioneering development’ and ‘shall be built around products that were never there before’.

14.2.2 Assessment of space ALSS technologies potential for Earth-based applications

This section introduces the assessment of space ALSS technologies potential for Earth-based applications, based on an ESA study[667] granted to Leoni Corporate Advisors (LCA)[668] in 2019. In particular, ESTEE led the technical side of this study for the assessment of the financial and business potentials of LSS technologies, and the collaboration with LCA notably established a high-level assessment methodology for LSS projects potential for Earth-based applications development[669].

The study was based on the observation that advancements of the space agencies' in terms of technological transfer of Earth-based applications was not explored enough. Obviously first because the mission of space agenices is not to develop such terrestrial solutions, and second, because of the ALSS community might be missing an appropriate framework to facilitate the involvement of the private sector to actively participate to the different phases of the spin-off of terrestrial technological solutions coming from the space application know-hows.

The scope of this project was to conduct an assessment of LSS projects with terrestrial applications under the MELiSSA framework, in order to: understand the commercial viability of the projects and potential financing source; and identify an evolutionary scenario of the existing MELiSSA framework to ensure its long-term sustainability[670]. In particular, ESTEE developed the technical evaluation methodology for the study[671], which covered the assessment of 9 LSS projects with terrestrial applications, covering a wide range of LSS categories and technologies: urine treatment, nutrient recovery, water recovery and recycling, photobioreactor, advanced controlled systems, as well as intensive greenhouse systems for food production and a pharmaceutical product. Assessment was based on both technology and business maturity aspects.

Projects leaders were distributed in 'LSS early starters' or 'LSS market makers'. LSS early starters had a high-level business idea but usually no business plan in place, and also missed a clear business case that is yet to be defined. Their product or service was either at a prototype level or none is available, and their time-to-market is longer than 2 years. The appropriate framework with this pre-seed level of maturity was incubation. ACE market makers had a well-defined business case and a detailed business plan, value proposition and business expertise in management team, and presented a MVP with a reasonable time-to-market (<1 year). The appropriate framework with this seed/scale-up level of maturity was investment facilitation. A subset of assessed projects could be selected to pilot n ew framework; early starters would most benefit from incubation, while more mature ventures can face investors.

The study found that technological reliability, effectiveness, robustness and readiness levels were generally high, while business maturity was uneven among the assessed projects. From a financial standpoint, the study deemed Venture Capital as the investor category sporting the most critical mass and thus most attractive for LSS[672].

In conclusions, the study proposed a number of improvements to the MELiSSA business framework. One proposed improvement involved the selection of a number of pilot projects to test run the new framework (incubation and/or investment facilitation) for LSS early starters and market makers, while leveraging on the ESA ecosystem (ESA Business Incubation Centre, ESA Business Applications

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[667] Study for the Assessment of the Financial and Business Potentials of LSS Technologies – ESA AO/1-9556/18/NL/AT, ESA Express Procurement [Plus] – [EXPRO+].

[668] Leoni Corporate Advisors' website: http://www.corporate-advisors.eu

[669] Cf Annex J1 for the proposal, Annex J2 for interview grid and Annex J3 for a selection of confidential excerpts from the study.

[670] Cf Annex J1.

[671] Cf Annex J2.

[672] Cf Annex J3.

programme) for execution capabilities[673]. It should be noted that one of the assessed LSS projects was a urine-monitoring toilet device using CSEM sensing technologies, which teamed up with ESTEE for implementing the next prototyping phases, through the SUMIT project[674].

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[673] Ibid.

[674] Cf §9.

14.3 An introduction on the notion of circular economy[675]

During the last decade, the circular economy (CE) concept, based on a make, use and return model, has gained a lot of attention worldwide among scholars, business community, practitioners and policy-makers, and is currently promoted by the European Union[676], United Nations[677] and several business organisations around the world.

According to Ellen MacArthur Foundation (2016), CE can be presented as 'a model that decouples economic growth from resource constraints by reducing reliance on virgin materials. Instead, the goal is to keep materials functioning at their highest utility at all time, preventing would-be waste from reaching landfills'. The main point of the CE concept is to capitalise on material flow recycling and to balance economic growth and development with both environmental and resource use. This vision rests on three principles as set in Figure 51.

The scope of CE can be considered as quite close to IE ones[678], as it contrasts sharply with the linear mindset still embedded in most of today's industrial operations: the linear take-make-dispose economy, which wastes large amounts of embedded materials and energy. Thus, the concept is nested with other concepts like industrial symbiosis, eco-industrial parks, eco-cities, eco-industrial networks and ecological economics. Towards a quasi-cyclical economy, the aim of the CE is to keep materials for as long as possible before they are released into the environment or stored in landfills. Material flow accounting for measuring the CE is increasingly used at national level, like in Switzerland (Swiss Federal Statistical Office 2020).

CE is constructed from societal production-consumption systems aims at optimising the services resulting from the nature-society relationship. This is done by using cyclical materials flows, renewable energy sources and cascading-type energy flows (Korhonen et al. 2018). By promoting the adoption of closing-the-loop production patterns, it is seen as an operationalisation for commercial activities to implement the concept of sustainability (Ghisellini et al. 2016). Therefore, CE has been envisaged as a particularly promising concept precisely thanks to its capacity to attract the business circles to sustainable development (McKinsey Center for Business Environment, 2015).

Interestingly, Murray et al. (2017) defined CE as 'an economic model wherein planning, resourcing, procurement, production and reprocessing are designed and managed, as both process and output, to maximise ecosystem functioning and human well-being'. This definition applies particularly well to the scope of crewed ACE at habitat scale.

Despite this momentum, Kirchherr et al. (2017) provided evidence for the critics claiming that CE means many different things to different people. By analysing 114 definitions of CE, their findings notably indicated that it is 'most frequently depicted as a combination of reduce, reuse and recycle activities, whereas it is oftentimes not highlighted that [it] necessitates a systemic shift' (…) 'instead of incremental twisting of the current system'. The study presumed that significantly varying its definitions may eventually result in the collapse of the concept, hence a need for clarity through the promotion of concrete examples of circular solutions. Furthermore, the main objective of the CE seems to be economic prosperity, before environmental quality. In other words, ecological principles are not sufficiently implemented by the normal practices carried out through CE, everything, or almost, remains to be done.

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[675] This section consolidates the introduction of circular economy as described in Annex C2a-§7.3.

[676] In 2015, the EU Circular Economy Package framed the legislative context for closing the loop of product lifecycles (Hughes 2017).

[677] By extension, in response to the United Nations Framework Convention on Climate Change (UNFCC), participating countries created strategies for low-carbon development based on the application of the CE concept (UNFCC, 2016).

[678] Cf §2.2.1.

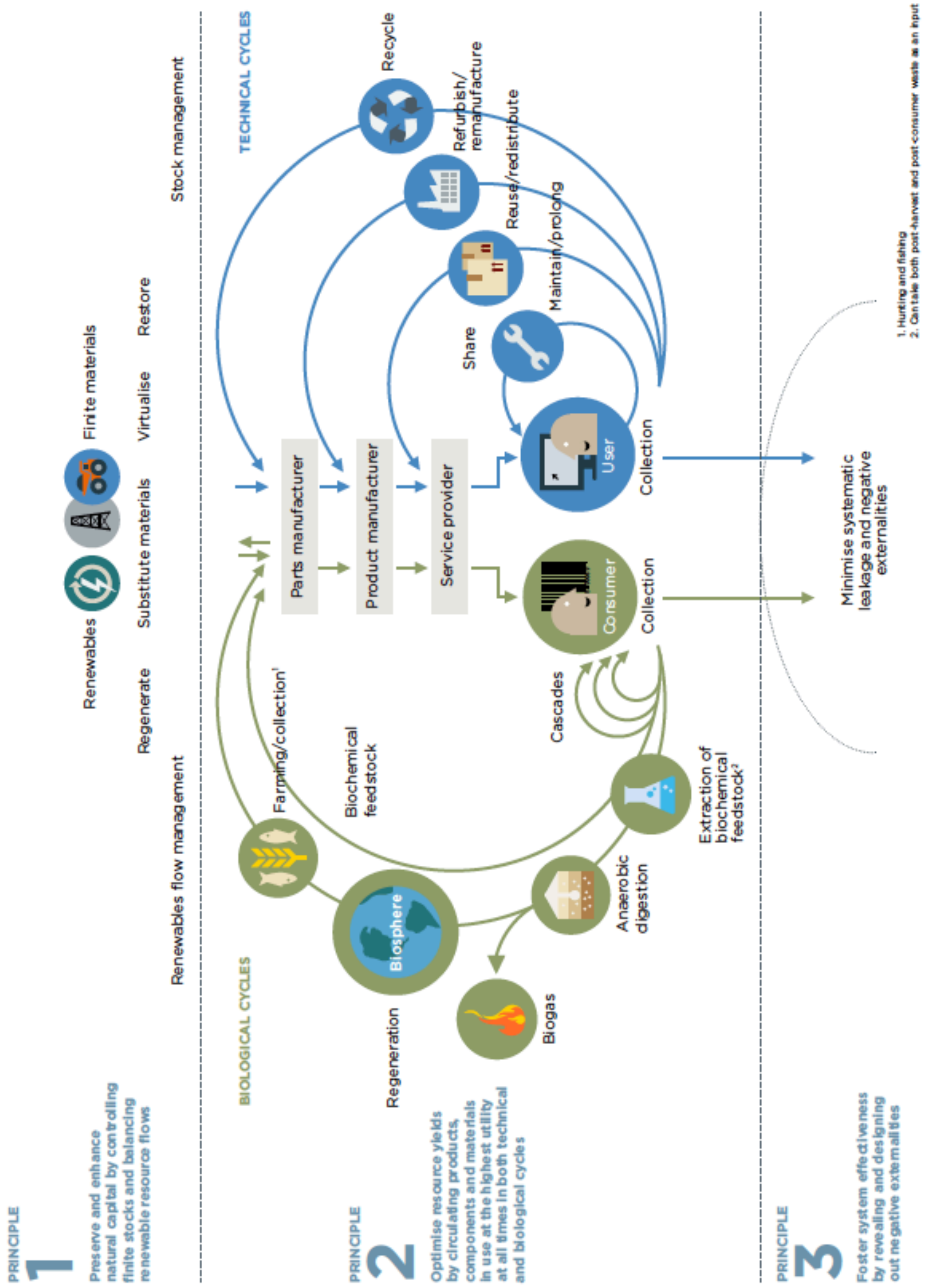

Figure 51: Outline and principles of a circular economy.
Source: Ellen MacArthur Foundation (2012), in collaboration with SUN and McKinsey Center for Business and Environment; Drawing from Braungart & McDonough, Cradle to Cradle (C2C).

Circularity evokes the dream of perpetual motion. But its rhetoric is sometimes misleading as circularity per se is not a guarantee of sustainability. In practice, any credible CE initiative should take into consideration the number of cycles and the importance of ultimate stocks (reservoirs). Otherwise, CE would become simply a modernised version of the end of pipe (§3.4).

As shown in the next section, ACE development can precisely illustrate such closed-loop solutions in a pragmatic way.

14.4 Contributions of ACE development to circular economy

Best practices developed in space projects in terms of circularity and sustainability are particularly valuable on the ground (Paladini et al. 2021).

The technological challenges for a crewed space mission are not insurmountable (Kliss 2016). In space, ACE represent a key element for the deployment of manned human missions. At the heart of ACE development lies an inextinguishable dream of resource circularisation, through the transformation of the organic waste of the crew into resources to regenerate what has been consumed. Therefore, the outcome of space ACE development underpins going full circle.

On Earth, natural resources consumption is growing in intensity and rapidity, while generating an increasing amount of waste. As a consequence, resource regeneration capacity is facing a mounting pollution and depletion. Most resources will not 'run out' completely, they will rather be more and more difficult to use and recycle with routine technologies. Closed-loop productions systems actively participate to the reintegration of the biogeochemical recycling functions of the biosphere (Fischer-Kowalski & Hüttler 1998). Their network forms an industrial metabolism taking place at different scales which are at the foundation of a truly circular economy.

In this context, the inhabitable ACE demonstrator offers a dual dimension to CE: on the one hand, it is a model for CE research at the conceptual level, whereas on the other hand, at the operationalisation level, it is a driver for sustainable terrestrial applications which are useful for implementing CE in an effective manner.

However, one can denote some conceptual lightness around CE when it comes to demonstrate convincing practical examples. Most of the time, no serious and sufficient technological breakthrough seems available with proposed CE solutions, in order to envisage a complete valorisation of key resources for ecosystems.

ACE-based hyper-efficient recycling systems can help material flows to recirculate and reintegrate the economy. Therefore, the concept of ACE provides a rigorous framework for pursuing a reflection on circular systems that goes beyond simple recycling processes with no optimal waste valorisation levels achieved at the systemic level. ACE thus provide an adequate experimental model to see how we will really recycle resources. Their development can compensate, at least to a certain extent, the relative lack of scientifically rigorous research frequently missing for many CE examples in their attempt to justify their positive environmental impact.

In different ways, the four science and technology clusters of the Oïkosmos agenda have potential benefits for the CE perspective: e.g. IE for decentralised waste treatment, systems biology for efficient food production systems and health management, ICT for system operations optimisation through smart monitoring of health and environmental data, closed and sustainable habitat based on the technology empowerment for self-sufficiency.

Consequently, both the user needs and the user experience of the innovative concept use in space ALSS should be capable to more easily be trickled down to terrestrial solutions for efficient and sustainable resource management.

The supreme objective of the contributions of ACE development – space-based or not – to terrestrial sustainability is to better tackle the circularisation of the economy through technological solutions that can be operationalised at various scales of the industrial system. In this respect, one challenge is to go beyond circularisation of flows within a CH, by making possible to upscale it at various stages of the supply chain of the industrial ecosystem. For instance, the application of decentralised systems at the level of the city would have a global impact in terms of resource use efficiency (Annex A-§7.4.2.1), knowing the people, resource and energy it concentrates.

The next sections describes concrete contributions of ACE development to CE in connection to the following topics: CE in space agencies' agenda (§14.4.1); biorefinery (§14.4.2); space 'meat' (§14.4.3); circular sanitation economy (§14.4.4); and eco-innovation (§14.4.5).

14.4.1 CE in space agencies' agenda

Paladini and al. (2021) demonstrated the readiness and compliance of the space sector to CE, arguing that the space sector represents a form of 'native environment' for CE so that the application of CE principles in space would in return enable us to better and more efficiently exploit them on Earth.

With the fast evolving environmental legislation and increased pressure from civil society, public organisations should have the capacity to quantify the environmental impact of their activities and products. To respond to this demand, ESA has been pioneering the application of LCA to space projects and developed guidelines for space system Life Cycle Assessment to map its supply chain and identify the areas of main environmental concerns (hot-spots) of their products and services along their overall life cycle (ESA LCA Working Group 2016).

According to ESA (2016), the space sector is a unique domain: it has low production volumes with high components generally having extremely high cost per weight, uses specialised materials and industrial processes and has impacts on environments so far not considered in the traditional LCA (e.g. direct emissions into the upper atmosphere). Another specificity is its long development cycles and R&D which represent a non-negligible portion of the total environmental impacts of ESA activities.

Carrying out an LCA study enables the meaningful benchmark of different design options for space systems, equipment or component from an environmental standpoint, based on the use of specific space materials, manufacturing processes or propellants, and to set up and follow up targets for specific terrestrial environmental impact indicators[679] such as ozone depletion, air acidification, particulate matter formation, global warming, human toxicity or marine aquatic ecotoxicity potentials, as well as specific flow indicators such gross water consumption, components left in space or disposed in the ocean or Al_2O_3 emissions in air.

Consequently, ESA is using LCA as a decision making tool to better communicate about CE models with the industry and policy-makers, in a harmonised and constructive way.

As a supersystem constituted by compartments (systems for transforming waste into resources), themselves composed of bioprocesses from ACE organisms (subsystems), MELiSSA illustrates the circularisation of material flows in a fully CE and 5R (Chen et al. 2020) compliant way[680].

As shown earlier[681], the wide scope of terrestrial applications from MELiSSA includes solutions which have no direct connection to CE, but that complement the CE principles implementation. For some time now, MELiSSA expertise on closed systems is used to design CE strategies[682], with projects such as NextGen[683], funded by EU's Horizon 2020 research and innovation programme, which aims to develop CE solutions for water management on Earth.

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[679] Therefore, the impacts assessment from space debris is excluded from the scope of such LCA.

[680] Paladini and al. (2021, p. 6): '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 [.]'

[681] Cf §14.2.2.

[682] Read the interview of Dr. Christophe Lasseur, Head of MELiSSA project in 'Closed-loop systems that keep astronauts alive in space could inform circular economy strategies', published on 18.09.2018 by European Science Communication Institute: https://phys.org/news/2018-09-closed-loop-astronauts-alive-space-circular.html (last retrieved on 24.08.2021)

[683] NextGen (Horizon 2020 grant agreement No. 776541) website: https://nextgenwater.eu

ESA Business Applications programme[684] provides funding opportunities with strong terrestrial sustainability orientation, based on satellite data technologies. In general, the related space technologies encompass satellite Earth observation, which typically enables natural resources monitoring as well as data for air quality and CO_2 emissions monitoring and forecasting; and satellite communications, which enables communications with remote locations when no terrestrial network is available, and supports Internet of Things (IoT) by connecting networks of sensors used to monitor equipment. As an example, a late 2020 invitation to tender (ITT) for a feasibility study on space applications to circular cities[685] focused notably on the transition for public transport to zero carbon emissions and service optimisation[686].

Even more recently, another ITT, targeting specifically CE[687], addressed topics such as food storage and supply chain efficiency optimisation, using new technologies such as sensors to precisely monitor changes in the resource quality, as well as blockchain and artificial intelligence to match supply to demand more accurately and minimise the waste generation. It also tackled the CE issue covering city-scale resource management, nutrient flows, and reverse logistics using digitally enabled technology solutions to enable/enhance collaborative, sharing and on-demand economy. Finally, the business opportunity addressed how to use resources mapping and tracking to design household waste collection systems with maximal recycling, as well as IoT to collect data on product elements location, functionality and working conditions through sensors.

Sanitation is also an important issue for astronauts in space[688]. In 2018, ESA teamed up with Toilet Board Coalition (TBC)[689], a global business partnership based in Geneva, for exploiting space technologies to address the most pressing sanitation challenges around the world[690], tackled 'digitised sanitation systems that optimise data for operating efficiencies, maintenance, plus consumer use and health information insights'[691]. In this respect, ESA pursued a feasibility study, started in 2020, on integrated applications for sanitation economy[692] focusing on geographic area in developing countries where both smart and circular sanitation economies can be demonstrated, with solutions providing the public toilet network users with smart health monitoring for rapid response to disease outbreaks, real-time environmental monitoring of water quality to assist in the detection of contamination; as well as advanced decentralised faecal sludge treatment generating electricity and producing carbon by-products. The space services for the study notably required in-situ (sewage/soil/water) sensors communication to data repositories; Earth observation imagery as inputs to diseases early warning models; and georeferencing to collect in-situ sensors' data. These space technologies shall play a key role in the transformation of sanitation system into an early warning detection system for health issues, and enable satellite monitoring of natural resources, such as water and soil.

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[684] ESA Business Applications aims at combining existing space assets with terrestrial technologies to deliver sustainable services for the benefit of user communities, see: https://business.esa.int

[685] Invitation to tender on space applications to advance innovation on circular cities of the 04.12.2020 from ESA business application website: https://business.esa.int/funding/invitation-to-tender/circular-economy (last retrieved on 23.09.2021).

[686] The related space technologies included Earth observation imagery (e.g. for traffic management), satellite navigation (e.g. for tracking and tracing vehicles or freights, and for navigating autonomous vehicles and drones, for geo-referencing sensor data related to infrastructure condition) and satellite communications (e.g. for distributing updated messages to all vehicles, for enabling emergency communications and alert services in remote areas).

[687] Invitation to tender on CE of the 03.05.2021 from ESA Business Applications website: https://business.esa.int/funding/invitation-to-tender/circular-economy (last retrieved on 23.09.2021)

[688] Cf §9.

[689] TBC website: https://www.toiletboard.org

[690] 'European Space Agency and the Toilet Board Coalition Partnership', published on 20.06.2018 on ESA Business Applications news feed: https://business.esa.int/news/ESA_TBC_partnership (last retrieved on 23.09.2021)

[691] Cf in particular the discussion on circular sanitation economy in §14.4.4.

[692] Space for Sanitation project launched in 2020 on ESA Business Applications website: https://business.esa.int/projects/space-for-sanitation-woodco (last retrieved on 23.09.2021)

Other contributions to CE from space ACE include a NASA-based technology[693] used to transform exhaled CO_2 is into food and bio-based products or to make plastic more biodegradable. Similarly, NASA is offering grants programme for closed-loop projects such as ‘Synthetic biology for recycling human waste into food, nutraceuticals, and materials: closing the loop for long-term space travel’[694], which are perceived as effort towards the beyond Earth CE[695].

14.4.2 Biorefinery

The emerging field of biorefinery provides interesting CE-related solutions, most particularly in the framework of ACE development (Annex A-§7.4.4). The core principle of biorefinery, arising in the wake of IE and of the bioeconomy, consists in exploiting and valorising any parts or residues of fresh biomass and residues in an industrial metabolism perspective (Octave & Thomas 2009). The main goal of biorefinery is to substitute oil products (including their associated intermediate chemicals) by biobased products, thus enabling the operationalisation of CE subloops. Meylan et al. (2015) gave an overview of the field of CO_2 utilisation in the perspective of IE[696]. They analysed capture at large sources, direct air capture and a bioenergy with carbon capture, as well as utilisation through processes such as solar fuel synthesis, mineralisation, polymer synthesis and biological utilisation. Oïkosmos Report §7.4.4 describes the strategies for CO_2 valorisation that could be relevant in the context of ACE and CH.

Microalgae cultivation, including in closed systems such as photobioreactors or thin-film bioreactors, present a potential for CO_2 capture coupled with wastewater treatment with a high yield per unit of light received, and also are a possible source of bioenergy (Razzak et al. 2013). Life-cycle based biorefinery studies showed promising bioprocesses intensification from sustainable microbial conversion of CO_2 (Mussatto et al. 2021).

As biological processes are essential to ACE development for the continuous production of various products from diverse biomass resources, implementing the biorefinery concept can increase the recycling level of the organic compounds found in biomass. One example is the bioconversion of lignocellulosic material from inedible biomass (Menon & Rao 2012) into value-added bioproducts, such as chemicals, materials or biofuel.

Production of nutrients such as microbial proteins for food and feed from atmospheric CO_2 capture, using electricity, water, hydrogen-oxidising micro-organisms and fertilisers in a bioreactor, in a closed loop system, with high production yield and low water and land requirement (Sillman et al. 2019). Other study demonstrated that waste streams containing different forms of nitrogen (including urine) could be used as a nitrogen source for microbial proteins production (Yang et al. 2021).

For space missions, electrochemical conversion of carbon dioxide can be used for chemical synthesis of carbohydrate such as sugars and glycerol are among the most energy efficient compared to storing prepackaged food, artificial-light grown Spirulina platensis, or microbial electrosynthesis (García Martínez et al. 2021).

In the context of closed systems, ACE biorefinery can create new building blocks from raw materials

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[693] Victoria Masterson, ‘This NASA-inspired technology converts carbon dioxide into food. Here’s how.’, published on 20.07.2021 on World Economic Forum website: https://www.weforum.org/agenda/2021/07/nasa-technology-converts-co2-into-food/ (last retrieved on 24.08.2021)

[694] See short description of this early-stage technologies R&D programme led by Prof. Blenner of Clemson University doted with $1.6M and part of NASA 2015 Space Technology Research Opportunities: https://www.nasa.gov/feature/synthetic-biology-for-recycling-human-waste-into-nutraceuticals-and-materials-closing-the/ (last retrieved on 24.08.2021)

[695] Madeleine Cuff, ‘The final frontier for the circular economy? NASA awards grant for poo-to-food research project’, published on 18.08.2015 on BusinessGreen online magazine: http://www.businessgreen.com/bg/news/2422325/the-final-frontier-for-the-circular-economy-nasa-awards-grant-for-poo-to-food-research-project (last retrieved on 24.08.2021)

[696] Cf §2.2.2.4.

and waste valorisation in order to maximise resource circularisation in the perspective of CE.

14.4.3 Space 'meat'

While microalgae like spirulina have been advocated for space diet by NASA and ESA since early 80s, space activities in 'clean' animal protein emerged only very recently (Ackerman 2019). In the challenging perspective to feed one million people on Mars within a century, Cannon and Britt (2019) discussed alternatives complementary to plant-based food production, with a Martian diet based on insects product and cellular agriculture. The latter could enable protein production from cultured cell feedstocks (cyanobacteria, cultured meat, cow-less milk, etc.) mostly from ISRU. Therefore, if spirulina can be used as food supplement, for the valorisation of urine nutrients or for bioenergy production, its space applications include in addition synthetic meat culture. Indeed, hydrolysed nitrogen-fixing cyanobacteria are recommended as cultured solution, as they represent the 'greenest' feed of meat culture according to LCA studies (Tuomisto & Teixeira de Mattos 2011; Scharf et al. 2019). Concretely, the overall environmental impacts of cyanobacteria-based cultured meat production are substantially lower than those of conventionally produced meat in terms of CO_2 emission per kg of cultured meat, as well as for energy, water and land use. Developing synthetic meat production capacities is therefore another synergetic endeavour in the perspective of CE both in space and on Earth.

14.4.4 Circular sanitation economy

The advent of the CE thinking is rapidly changing society's expectation on wastewater treatment, more and more considered as a resource, not only as a source of water but also of nutrients, chemicals and energy. Also, the increased wastewater analytical capacities enabled water contaminants monitoring and removal, in order to safeguard environmental and human health.

Therefore, another case study is circular sanitation economy, which should be considered as sustainable, profitable, and largely untapped. In their study on the topic, Toilet Board Coalition (TBC) (2016) pointed out that toilet resources are major parts of biological cycle and remain vastly unexploited, with significant leapfrog opportunities for low-income economies. To them, CE can transform sanitation from costly to value-adding service through integrated resources management (recovery for water and nutrients, energy efficiency) with self-sustaining facilities and operations along the sanitation biocycle. The associated applications for wastewater nutrients recovery are part of the typical decentralised systems solutions for ecosanitation based on ACE development described in Annex A-§7.4.

In another report on the digitisation of sanitation, TBC (2016) argued that mobile and digital applications could transform the toilet from waste hardware into a centre of health and information. TBC thus envisions more sanitation resources to be available in the future through innovative products based on information/health data management. According to them (2017), a health-monitoring toilet, like SUMIT as described in §9.2 and §9.3 should become one of the pillars of a smart sanitation economy (see Annex D3, p21, for SUMIT contributions to CE). The latter is a sub-loop of the circular sanitation economy, which is fed by data on user sanitation health and habits, and sanitation system function, all collected through sensors. In particular, mobile money (smartphone-based payments) and IoT are global development megatrends that are mostly unexploited in sanitation systems. In the last few years, mHealth applications for sanitation have been poised for dramatic growth. Therefore, the market value of health data generated from smart toilets is expected to rise significantly. Specifically, sensors in the household, business, and public toilets will capture data from toilets and transmit it to connected devices and networks. Three categories of data can be envisaged: a) health data will inform individual users about their health status, as well as public health policy makers about disease prevalence and use of pharmaceutical substances; b) consumer use data will provide insight about consumer behaviours, which will be further mined through marketing and targeted advertising; c) finally, system operations data will inform toilet manufacturers, operators, and service companies on the need for toilet cleaning, maintenance, and repair. Data on waste generation will inform companies responsible for waste collection and for waste processing/valorisation, and companies or individuals engaged in urban farming utilising resources recovered from toilet waste; Among the key findings of TBC (2017) are the facts that circular sanitation business models can be profitable at lower cost than traditional sanitation systems, within rapidly scalable 'new grid' (new network of material, energy, and info flows), and present new opportunities within new business ecosystem (entrepreneurs, utilities, large business, cities), thus creating a working biological cycle, in which nutrients are returned to the biosphere, most often to the soil.

Finally, the SUMIT device described earlier[697] offers technological solutions that illustrate the relevance of Earth-based applications of ACE to terrestrial sustainability, and that are not dependent on space-based technologies such as the above-described examples from the ESA Business Applications programme.

14.4.5 Eco-innovation

Inventions from space ACE development need to be transformed into innovative solutions on Earth and should also directly contribute to economic growth and societal well-being[698]. With its closing-the-loop approach, the value of ACE relies particularly on their capacity to deal with limited resources, using systems for resource recovery, which can improve life and environmental conditions in a purely terrestrial context. Yet, ACE development is not just about resource valorisation but also about know-how valorisation, through technology and knowledge transfer from space down to Earth. As a leading technological platform for the study of circular systems[699], the ACE demonstrator is a useful tool to conceptualise the opportunities for knowledge and technology transfer, and provides multiple modalities of use, operational activities and services to the actors of the Research-Innovation-Market value chain.

Turning conceptual R&D into value proposition implies the operationalisation of ideas into an invention and later into a market success. This involves a dual process first for exploring business model and market segmentation and then exploiting innovation and institutional support (Osterwalder et al. 2020).

With the New Space era, the role of space agencies at global level has changed, and now imply new kinds of relationship with the private sector, mainly through public private partnership and co-development[700]. This also applies for ACE development as shown in Figure 47[701]. New business frameworks for ACE 'market makers', as such mentioned earlier[702], can facilitate investors engagement thanks to their more mature venture profile. A complementary road is the one of business incubators, such as ESA and SSO have been putting in place in Switzerland with ESA-BIC[703], which incubated more than 50 start-ups so far in less than 5 years of existence, which raised nearly 200 MEUR of third party money.

In the context of terrestrial sustainability, space ACE advancements should be considered as drivers for eco-innovation[704]. Eco-innovation encompasses the acceleration of the technology transfer of

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[697] Cf §9.2 and §9.3.

[698] Cf §14.2

[699] Cf §6.

[700] Cf §15.1.

[701] Cf §13.2.2.

[702] Cf 14.2.2.

[703] ESA BIC Switzerland (Business Incubation Centre): https://www.esabic.ch.

[704] Cf Annex A-§15.

responsible solutions up to high market readiness levels, in order to achieve effective market diffusion, appropriation and profitability.

In the context of Oïkosmos, eco-innovation processes enhance the spin-out of a variety of Earth-based applications from space ACE[705]. ACE-related terrestrial solutions empower some of the essential dimensions for effective decentralisation of waste treatment[706] and self-sufficiency at habitat level[707]. The large-scale dissemination of such solutions seems to be of fundamental interest in order to progressively achieve a CE. In this respect, both ACE demonstrators and Earth-based applications of space ACE have the potential to facilitate the operationalisation of CE.

In the case of financing of technology demonstrators are key (but costly) to developing new concepts and attracting private investors, as well as actors of the CE. One of the challenges for start-ups is to use the optimal managerial model without losing speed of execution and agility. In this purpose, an ACE demonstrator, which combines a minimal CH in terms of size, with maximal material closure level, gives an appropriate framework for lean management, of which one of the golden rules is ‘reduce or remove everything which is not added value’, in this case for achieving self-sufficiency. Nonetheless, ACE development should in parallel ensure achieving real impact, not focusing on showcasing (festivals and promo building) but with widely diffused and/or large-scale terrestrial applications.

However, ACE-related fields depends on actors along the entire innovation value chain, which typically consists on the following phases: R&D to technology transfer, to (pre)industrialisation, to commercialisation. And despite the potential for terrestrial applications remains high, many ACE-based solutions are still at the early start of their industrialisation and commercialisation phases[708]. Eco-innovation is all about execution, and execution requires a business mindset for enabling future ACE early starters to become ACE market makers and go beyond the technology showcase and convert R&D into impactful commercial development with well-defined products. In any case, ACE early starters most benefits from incubation, while more mature ventures can face investors[709]. For this reason, and in order to fill the gap of the ‘missing preindustrialisation link’ in the ACE eco-innovation value chain and effectively operationalise CE, an increased priority should be put on making these solutions more marketable, affordable and sellable.

ACE inspiration capacity is clear, and so it is for technological development. Now the urge is to focus more on the business maturity (‘market readiness level’, MRL) of Earth-based applications of ACE. Successful attraction of the new actors of CE might need a simpler pitch for an ACE-related technological solution whose business development just started, based on well-described USP rather than on a too technological-centred speech. This implies to switch the focus in due time from the technical aspects (technical features, TRL) to the business maturity of the LSS-related terrestrial applications and spin-offed projects, with a particular emphasis on their respective economic feasibility, MRL and early market validation (if already effective) in order to get the necessary investment for ensuring the market viability, as well as the long-term affordability and profitability.

On the basis on the findings from the workshop session ‘How to attract CE actors’ at MELiSSA conference 2020, which was chaired by the author of this thesis, the first step to put CE into practice at a broad level requires a cognitive leap for non-space companies to realise that they are concerned by the eco-innovation processes on circular systems such as space ACE.

At the global level, European ACE community has a key role to play to federate its members and

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[705] Cf §14.2 and Annex A-§15.

[706] Cf Annex A-§7.4.2.

[707] Cf §13.4.

[708] As shown in the outcome of the ESA study introduced in §14.2.2.

[709] Ibid.

partners, attract new actors active in CE, and develop new businesses beneficial to the citizen and with positive impact for terrestrial sustainability. In this purpose, some of the conclusions the above-mentioned workshop session recommended the following actions:

- consolidate the ecosystem of ACE by strengthening the innovation ecosystem value chain with national anchors, to facilitate the integration and better attract CE actors, which consisted of a bottom-up exercise for the Swiss Position Paper on ALSS and of a top-down one with ESA project on LSS technology business and financial potential assessment. In particular, continue lobbying at all levels: National space delegation; Local and regional authorities; national innovation agency; citizens, etc.;
- elaborate pitches showing the business potential, MRL and contributions of MELiSSA Earth-based application to the attention of CE actors;
- elaborate and regularly update a report on the recent success stories related to spin-offed activities in sectors connected to CE and map them by topic (microbial biomass valorisation) or by market sector (water recycling, health monitoring);
- organise new editions of the ESA Closed Habitat Forum;
- bridge scientists, engineers and industrial with innovators and managers to foster the spin-out and spin-in of technical solutions and cross-fertilise space and terrestrial dimensions of ACE;
- leverage synergistic interactions to give CE actors access to gateways (i.e. Semilla IPStar, ESTEE) that facilitates the dialogue and enhance collaboration opportunities identification and implementation;
- better connect the benefits of ACE technology to health (health safety, monitoring, connection to COVID-19 confinement and lockdown), health being an essential part of a virtuous CE loop;
- reinforce the role of ground demonstrators, at the interface of the space and terrestrial dimensions of ACE development, as a platform for attracting the actors of CE and make them join the MELiSSA community;
- clarify the purpose and scope of space ACE development to CE actors: e.g. make a distinction between space exploration and settlements.

14.5 Final considerations

Is the industrialisation of space a form of human progress and a strategic necessity? Does it target only a privileged class of wealthy people? How can we explain the ambiguity surrounding the perception of space exploration, seen both as a source of significant technological and societal progress, but also as a pointless and disconnected quest with no interest for Earthians?

As per Walker and Grandjou (2017), ACE development such as MELiSSA community ones are ‘paradoxical, promising technologies with which to escape from the Earth and through which it may be sustained’. This paradox is seen here as an opportunity.

Space ACE are necessary in the first place for space exploration rather than space colonisation[710]. In other words, the main point of ACE development is not primarily based on the perspective that Earth might cease to function properly at some point in the future. Still space exploration is about preparing the future, in a sense that it should benefit the Earth right now and be instrumental for the betterment of society.

Space is only one of the applications of ACE. Clearly, the circular systems developed by space ACE promoters for solar system exploration exemplify this attempt to reconcile a space exploration compatible with the safeguard of Earth.

The meaningfulness of the dimension of terrestrial sustainability, which could be perceived as a contradiction at first glance, became progressively a conventional argument and postulate among the space ACE and ALSS communities, as well as the space industrialisation advocates.

Space technologies helped in the past, helps now and will increasingly help. If nobody went to Mars yet, in the meantime, several MELiSSA technos have been successfully spin-offed and many others will. MELiSSA and ESA CE programme exemplified how space activities can play a role for developing countries in general[711] and in a sustainability perspective.

ACE advancements should not be seen as a limitless technological expansion in space. Compared to the typical New Space promoters, current ACE projects such as MELiSSA and ESTEE are more oriented towards international cooperation and promote ecotechnologies which have the capacity to empower the transition to a CE on Earth.

In conclusion, even if manned long-duration and remote space missions would not be carried out, research for hyper-efficient space ACE and ALSS is worth doing anyway not only due to the growing constraints on Earth, but to their potential for the sustainable resource management on Earth. Therefore, this research anticipates that ACE components will be developed in any case for their relevance for terrestrial sustainability, and their market applicability into everyday life.

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[710] Cf §15.6.

[711] As stated online by ESA in Science and exploration section: ‘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’:

https://www.esa.int/Science_Exploration/Human_and_Robotic_Exploration/Research/Life_support (last retrieved on 15.10.2021).

15 Envisaging sustainability (in the human life perspective) at cosmic scale (RO3.3)

Eventually, with the benefit of hindsight from the overall outcome of this research, this thesis discusses the possible ways to envisage sustainability (in the human life perspective) at cosmic scale (RO3.5).

In the context of the spectacular development of the commercial use of space, this last chapter is a foresight exercise which discusses the compatibility of space exploration with sustainability and the possible evolutions of space ACE and ALSS development, including their impacts on the way we can envision sustainability at space level.

It first introduces the emerging field of New Space (§15.1). It then discusses the rise of space tourism (§15.2) and examines space colonisation as a necessary expansion of humanity in the solar system (§15.3). Furthermore, it describes the approach of space sustainability (§15.4). Subsequently, it mentions the extension of the notion of space sustainability to cosmic scale (§15.5). Finally, it considers the contributions of ACE development to space sustainability (§15.6).

15.1 The emergence of New Space[712]

Humankind has always been fascinated by the sublimity of the sky, the stars and the Universe. Appetite for human space exploration remains, and will remain. Simply because it is a powerful source of inspiration for people. At the beginning of the 21st century, its advocates see it as relevant to the development of society. In the case of space conquest, the major stakes are (Pellerin et al. 2013; Bainbridge 2009): 1) scientific and technological (advancement of knowledge, stimulation of the research-innovation-market value chain), 2) economic (industrial development of the Ariane or SpaceX types, vast civil application markets, e.g. through space-based telecommunication), 3) environmental (satellite-driven Earth observation) 4) geostrategic (military application aspects, technological showcase, prestige through recognition of a technological power status, surveillance purposes through the installation of remote tracking and warning stations for potentially dangerous asteroids[713]) and 4) societal (source of inspiration and education, for example to encourage the next generation of scientific and technical training courses).

Historically, the space sector was traditionally steered by national space agencies. In the past two decades, a paradigm shift happened with a continuing and now extremely significant involvement of private actors[714]. Space is no longer the sole prerogative of states and is becoming a large-scale commercial and industrial activity. Private and public investments in space are multiplying.

The term 'New Space' was coined to describe this changing of global space sector and refers to innovative technologies developed through entrepreneurial activities, as well as new research, business and financing models from private stakeholders (Paikowsky 2017). The expansion of New Space businesses concerned mainly launching capacity and services to facilitate less costly access to space, as well as Earth observation and satellite telecommunication. A big example remains the CubeSat development, manufacturing and standardisation, sometimes integrated with operation services. Apart satellite miniaturisation, space rocket reuse is another illustration of New Space development.

Even if with such examples the concept is now widely diffused, the borders of New Space activities with historical commercial space activities are sometimes blurry and needs clarification. In a nutshell, New Space is characterised in priority by the entrepreneurial component of its technology development (Peeters 2018). Therefore, rather than being a 'renewal', it should be considered as an opening of the space market to new players.

New Space expansion benefitted from the NASA decision to cease its Space Shuttle programme in the 2010s. Today, a growing number of space projects primarily rely on public-private partnership initially generating products, materials and equipment financed by public budget. Entrepreneurs reduced their costs by benefitting from the space agencies' funding (e.g. in terms of launching capacity), while the latter can rely on solutions developed in a faster, efficient and often more affordable manner, turning the collaboration in a win-win situation. As a second step, new market applications are privately financed to offer space technology for commercial use, where New Space companies will further develop based on market demand.

According to an estimate by the investment bank Morgan Stanley in 2019, the turnover of the New Space industry amounted to 350 billion USD, and should exceed one trillion US dollars (USD) in 2040[715],

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[712] It is to be highlighted that the Oïkosmos project and ESTEE activities have been present at one of the New Worlds Conference 2017 (Besson & Erkman 2017), which is dedicated to the development of New Space, with an audience composed of high level representatives from the key players in the field (SpaceX, NASA, Space Frontier Foundation, etc.).

[713] Activities of the NASA's Near Earth Object Program: https://cneos.jpl.nasa.gov (last retrieved on 13.09.2021).

[714] Toivonen (2020b, §7): 'The era of the New Space economy has brought new private actors to the formerly government monopolised arena and, aside from space tourism, there is vast economic potential in future space mining and private satellites supporting the technical functionality of the Earth.'

[715] Space: investing in the final frontier, Morgan Stanley Research forecasts summary published on 24.07.2020:

projections that are also forecasted by UBS (2018). As an example of this trend, NASA recently contracted with US private actors to develop designs of space stations and other commercial destinations in space in late 2021 for over 400 million USD to ensure a transition of activity from the International Space Station to commercial destinations[716].

In the end, New Space phenomenon fosters the growth of the space ecosystem, through the integration of new start-ups that have the capacity to pave the way for business success more easily than older companies, despite their initial know-how gap. Particularly, newcomers' success stories from the New Space do not depend on organisation age and size as it used to be (Denis et al. 2020). New Space expression also refers to the new phase of space conquest that has been underway for the last decade or so, which is characterised in particular by the decisive role played by private actors financed by billionaires, e.g. new companies such as SpaceX[717] created by Elon Musk (Tesla), Blue Origin[718] created by Jeff Bezos (Amazon) and Virgin Galactic[719] created by Richard Branson.

Obviously, they still have to follow the rules of government, but their business-oriented nature made them – or even force them when private equity-driven – to become more flexible and agile than public-funded projects. In short, New Space actors are more user-centred and show an unquestionable open-mindedness.

Nevertheless, New Space actors are pushing the limits of the historical international space treaties and intergovernmental conventions. For instance, US space mining actors lobbied to US Congress and obtained in 2015 the US Commercial Space Launch Competitiveness Act (H.R.2262 - 114th Congress 2015), an act which, while recognising the restrictions of the Outer Space Treaty according to which use of outer space is a global common, gives US citizens the right to exploit space resources under national laws (Clery 2017). Furthermore, even though there is no global consensus on international regulation of space resource use, some argue that it is better to start with space market development associated to imperfect regulation than to stay inactive (Jennifer et al. 2020). Nonetheless, space is not a place for business activity like any other. On the contrary, it should be preserved and become a shared resource, rather than be the subject of a gold rush pushed by country supportive to their national private companies effort, first there, first served.

Paradoxically, a somehow unexpected outcome of New Space development is how much governmental space agencies, private space actors and policy-makers have started to cooperate and support each other. At the same time, New Space is also contributing to the militarisation of space. Strategic and military space activities are actively pursued and we are currently witnessing a new arms race in space (Peperkamp 2020), with the USA, Russia and China as the main players[720].

Next section focuses on the New Space-driven rise of space tourism.

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https://www.morganstanley.com/ideas/investing-in-space (last retrieved on 05.10.2021).

[716] NASA Selects Companies to Develop Commercial Destinations in Space, NASA press release published on 02.12.2021: https://www.nasa.gov/press-release/nasa-selects-companies-to-develop-commercial-destinations-in-space (last retrieved on 03.12.2021).

[717] SpaceX website: www.spacex.com.

[718] Blue Origin website: www.blueorigin.com.

[719] Virgin Galactic website: www.virgingalactic.com.

[720] For instance, the US Space Force became operational in late 2019, creating the first new branch of the armed services in more than 70 years: https://www.spaceforce.mil/About-Us/About-Space-Force/History/ (last retrieved on 05.10.2021).

15.2 The rise of space tourism

New Space industry shows nowadays a continuous growth of commercial space activities such as space tourism (Collins & Autino 2010; Seedhouse 2008), which has further progressed since it was initiated by Denis Tito in 1998 (Reddy et al. 2012). Firstly, the target destination has been near-Earth space.

With these New Space companies, there is currently a growing market targeting relatively wealthy customers for suborbital spaceflight. In 2021, the renewed race to space has gathered a lot of media attention, with other large fortunes Richard Branson and Jeff Bezos celebrated their manned suborbital spaceflight with their respective companies, Virgin Intergalactic[721] and Blue Origin[722], within a few days of each other, achieving major milestones after respectively 17 and 21 years of massive investments and engineering. In mid-September 2021, SpaceX launched its first tourist mission, called Inspiration4, the first in history to send only novices into orbit, with no professional astronauts on board[723, 724]. The 4-people all-civilian crew spent three days alone in orbit around the Earth, after having trained for only a few months, thus paving the way for space tourism, even though we are way beyond a democratisation of it with a seat price estimated at 40 million dollars[725].

Based on NASA announcement to work with a private space manufacturer to attach a habitable commercial module to the ISS[726] later in order to foster a robust low-Earth orbit economy, one could envisage that New Space actors would target to build a kind of space hotel on the Moon or Mars at some point.

In a shorter-term perspective, Collins and Autino (2010) discussed the socioeconomic aspects of space tourism for employment, economic growth and for preserving peace by eliminating any need for 'resource wars'.

Interestingly, the economic expansion of larger-scale space tourism industry is expected to be beneficial through less expensive and more widely available space application due to cooperative schemes, resulting in more environmental knowledge and protection of the Earth (Toivonen 2020b). As pointed out by Toivonen (2020a), space tourism, characterised by the adventure-seeking individualism of its customers and its potentially lucrative private business prospects[727], raise scepticism and ethical concerns[728] from the greater public. For some authors, it is rather obvious that space tourism will not be part of sustainable tourism (Peeters 2018), notably because it is a resource-intensive and polluting activity. For others, the spatiotemporal framing of space tourism, implies that we attain both a

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[721] Virgin Galactic press release from 11.07.2021, 'Virgin Galactic Successfully Completes First Fully Crewed Spaceflight': https://www.virgingalactic.com/articles/virgin-galactic-successfully-completes-first-fully-crewed-spaceflight (last retrieved on 13.09.2021).

[722] 'Jeff Bezos launches into space on Blue Origin's 1st astronaut flight', published on space.com magazine on 20.07.2021: https://www.space.com/jeff-bezos-blue-origin-first-astronaut-launch (last retrieved on 13.09.2021).

[723] Kenneth Chang, 'Inspiration4 Astronauts Beam After Return From 3-Day Journey to Orbit', published on 18.09.2021 in NY times: https://www.nytimes.com/2021/09/18/science/spacex-inspiration4.html (last retrieved on 20.09.2021).

[724] See press release from 19.09.2021 'Inspiration4 Crew Makes Evening Splashdown, Completing World's First All-Civilian Orbital Mission to Space': https://inspiration4.com/press/kennedy-space-center-fl-september-18-2021--after (last retrieved on 20.09.2021).

[725] Ibid. note [723].

[726] NASA press release of the 04.01.2020, 'NASA Selects First Commercial Destination Module for International Space Station': https://www.nasa.gov/press-release/nasa-selects-first-commercial-destination-module-for-international-space-station (last retrieved on 13.09.2021).

[727] Toivonen (2020a, p. 1): '[I]n light of the current megatrend of environmentalism, different space tourism activities are facing climate change-related challenges to convince the greater public of their necessity, especially as the high cost involved for suborbital space travel limits it to a niche adventure activity for the wealthy.'

[728] Toivonen (2020a, p. 14): 'Ethical concerns were raised in connection with further developments in space tourism, such as growing rich versus poor inequalities, responsibility for compensation and fairness in determining ownership of the space environment (especially relevant with the discourse of space colonisation, hypothetically in the future providing a base for mining minerals to preserve the Earth's natural resources) and ultimately saving the human race in the case of a global catastrophe.'

sustainable state and a sustainable trajectory (Spector et al. 2017).

With this context, it is difficult to forecast whether space tourism will develop on a large-scale or if such venture will fall short, due to its significant environmental impact on Earth and to the potential lack of space access due to increasing risk of collision with orbital space debris[729].

Contrarily to space tourism, which may be considered the ultimate luxury tourism experience (Toivonen 2020b), a form of individualism and search for a kind of absolute emotion and feeling, space agencies embracing science-driven space exploration implies to implement a collective and altruist approach.

In particular, due to its short duration, suborbital and orbital space tourism seems to have few to bring to ACE development compared to space exploration – with the exception of space hotels –, but there are few doubts that these kinds of space flights will advance spacefaring technologies. In any case, the development of space tourism questions the sustainability of space exploration, as further detailed in below[730], questions which shall apply to any space development and in particular to the extension of human life beyond the biosphere, as discussed in the next section.

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[729] Cf §15.4.

[730] Ibid.

15.3 Space colonisation considered as a necessary expansion of humanity in the solar system

Should the colonisation of space be considered a necessary expansion of humanity in the solar system? Indeed, as some advocate that it is vital to spread life in the Universe (Mautner 2010). Space colonisation was notably promoted by the astronaut Buzz Aldrin (2013) and eminent physicist Stephen Hawking[731], who go so far as to believe that human life in space is essential to ensure its long-term survival[732 733] – and that of other terrestrial species – far beyond the confines of planet Earth. This position was also evidenced by the omnipresent Elon Musk, multi-billionaire and CEO of SpaceX, who strives with every effort for making humans a multi-planetary species (Musk 2017). The determination of this genius entrepreneur[734] could well be decisive, as the colonisation of Mars and the establishment of a self-sufficient planetary base on Mars has become his obsession[735, 736].

To measure what he achieved with SpaceX, we can summarise that by winning a NASA tender in 2008 following the planned retirement of the US space shuttle[737], SpaceX managed to become the first private contractor to service the ISS in record time. The first refuelling took place in 2012[738], using its Dragon space cargo[739] and Falcon 9 launch vehicle[740]. In 2014, SpaceX began construction of its own spaceport in South Texas. To establish man on Mars with a view to actually colonising it, SpaceX then started a major project to develop the Mars Colonial Transporter (MCT), a monumental vessel capable of depositing one hundred tonnes of payload on Mars (!), allowing one hundred people to be transported per trip. With the MCT, SpaceX's vocation is affordable Earth-Mars transport, with a one-way trip envisaged in the order of $500’000 to $1’000’000[741], thanks to reusable ship components[742] and a very simple architecture. Musk deeply believes that by 2035 space rockets will carry thousands of travellers to Mars, enabling the development of a self-sustaining human colony (Andersen 2014). To achieve this

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[731] ‘Why We Should Go Into Space’, Stephen Hawking’s talk on the American National Space Society: http://www.nss.org/resources/library/spacepolicy/hawking.htm (last retrieved on 10.05.2020).

[732] Stephen Hawking (2015): ‘Sending humans to the Moon changed the future of the human race in ways that we don't yet understand. It hasn't solved any of our immediate problems on planet Earth, but it has given us new perspectives on them and caused us to look both outward and inward. I believe that the long-term future of the human race must be space and that it represents an important life insurance for our future survival, as it could prevent the disappearance of humanity by colonising other planets.’

[733] Stephen Hawking (2016): ‘We face a number of threats: nuclear war, global warming and genetically engineered viruses. Although the chance of disaster on planet Earth in a given year may be quite low, it adds up over time, becoming a near certainty in the next thousand or ten thousand years. By that time, we should have spread out into space and to other stars, so it would not mean the end of the human race. However, we will not establish self-sustaining colonies in space for at least the next hundred years, so we have to be very careful in this period.’

[734] Musk has also founded successful companies such as PayPal, Tesla and SolarCity, the first of which he sold to eBay in 2002 to make his fortune.

[735] ‘The thing that’s important in the long run is establishing a self-sustaining base on Mars’, on 332 of its biography (Vance 2005).

[736] Ibid., page 335 ‘I would like to die on Mars’, he said. ‘Just not on impact. Ideally, I’d like to go for a visit, come back for a while, and then go there when I’m like seventy or something and then just stay there.’

[737] See SpaceX press release from 23.12.2008, ‘F9/Dragon Will Replace the Cargo Transport Function of the Space Shuttle after 2010’: www.spacex.com/press/2012/12/19/nasa-selects-spacexs-falcon-9-booster-and-dragon-spacecraft-cargo-resupply (last retrieved on 10.05.2020)

[738] See NASA press release from 07.10.2012, ‘First Contracted SpaceX Resupply Mission Launches with NASA Cargo to Space Station’: www.nasa.gov/centers/kennedy/news/releases/2012/release-20121007.html (last retrieved on 10.05.2020).

[739] Detailed description of Dragon cargo: www.spacex.com/dragon (last retrieved on 10.05.2020).

[740] Detailed description of Falcon 9 launcher: www.spacex.com/falcon9 (last retrieved on 10.05.2020)

[741] ‘The thing that’s important is to reach an economic threshold around the cost per person for a trip to Mars. If it costs $1 billion per person, there will be no Mars colony. At around $1 million or $500,000 per person, I think it’s highly likely that there will be a self-sustaining Martian colony. There will be enough people interested who will sell their stuff on Earth and move. It’s not about tourism. It’s like people coming to America back in the New World days. You move, get a job there, and make things work. If you solve the transport problem, it’s not that hard to make a pressurized transparent greenhouse to live in. But if you can’t get there in the first place, it doesn’t matter.’, on page 333 of its biography (Vance 2015).

[742] Rocket reusability reduces mission costs by two orders of magnitude, to tens of dollars per pound of weight

stratospheric goal, crewed spaceflights are driven through SpaceX Starship program since 2018[743]. The SpaceX roadmap, even if constantly adjusted, includes as per mid-2021 a tourist mission around the Moon planned for 2023[744], followed by the sending of the first uncrewed starship to Mars in 2024[745], with the target of landing humans on Mars by 2026[746]. And so far, it is clear that with this exceptional person, nothing seems impossible.

Elon Musk's plan to prepare a long-term settlement alternative for humanity on Mars seems to go well beyond a purely tourist objective. As rationale for making life multi-planetary, Musk is not selling space as an R&D lab, or an enhancer for spin-off technologies (Andersen 2014). Instead, he foresees Mars colonisation as an 'extinction insurance' and believes 'going to Mars is as urgent and crucial as lifting billions out of poverty, or eradicating deadly disease,' [in order to] safeguard the existence of humanity, (…) in the event that something catastrophic were to happen, in which case being poor or having a disease would be irrelevant, because humanity would be extinct.'

Regarding the relationship between the rise of New Space and the future of space exploration, some authors consider that Elon Musk's vision 'Making Humans a Multi-Planetary Species' can be challenged but it still filled a gap left empty since the end of the cold war (Denis et al. 2020), as it addresses the key question of 'what do we want to do in space?', beyond developing commercial activities per se. Is the ultimate goal protection, exploitation or exploration?

Clearly, for space agencies, there is a general agreement that human space exploration is an essential objective for the future. The priority is near-Earth space (a few tens of thousands of kilometres, where telecommunications, weather and observation satellites are located), then the Moon, certain asteroids and the planet Mars. At present, the missions eyeing the exploration of the Moon, Mars and even of various satellites and asteroids have essentially scientific objectives (e.g. planetary geosciences, exobiology and origin of life). Moreover, the nature of any human space exploration enterprises should show a steady and continuous upward progression towards greater societal, scientific and technological development. Historically, space-based telecommunication and satellite-driven Earth observation are good examples of space development that have positive added-value not only economically but also societally with ubiquitous access to Internet, as well as environmentally with Earth protection based real-time monitoring of environmental pollution, climate change consequences and accurate weather forecasts. In addition to become a major decision-making tool for managing environmental issues on Earth, they have a potential for operationalising the CE concept as presented earlier[747].

On the other hand, actors from the New Space community justify human colonisation of space for environmental, industrial or commercial reasons, because it could, among other things, allow humans to preserve the Earth's environment by moving certain industrial activities into space such as asteroid mining (Andrews et al. 2015). The first approaches to prospecting for mineral resources on asteroids are currently being considered by space agencies like NASA[748], [749] and by companies such as

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[743] SpaceX Starship development history on Wikipedia: https://en.wikipedia.org/wiki/SpaceX_Starship_development_history (last retrieved on 13.09.2021).

[744] 'Elon Musk says SpaceX's 1st Starship trip to Mars could fly in 4 years' published on space.com on 16.10.2020: https://www.msn.com/en-us/news/technology/elon-musk-says-spacexs-1st-starship-trip-to-mars-could-fly-in-4-years/ar-BB1a72Tq (last retrieved 13.09.2021).

[745] Elon Musk's talk to 2020 Mars Society Virtual Convention, streamed on 16.10.2020: https://www.youtube.com/watch?v=y5Aw6WG4Dww (last retrieved 13.09.2021).

[746] 'Elon Musk is 'highly confident' SpaceX will land humans on Mars by 2026' published on CNBC network: https://www.cnbc.com/2020/12/01/elon-musk-highly-confident-spacex-will-land-humans-on-mars-by-2026.html (Last retrieved on 13.09.2021)

[747] Cf §14.1.

[748] 'La NASA envisage de capturer un petit astéroïde', published in Le Monde on 06.04.2013 : www.lemonde.fr/sciences/article/2013/04/06/la-nasa-envisage-de-capturer-un-asteroide_3155446_1650684.html (last retrieved on 13.09.2021).

[749] Asteroid Redirect Mission on NASA website, published on 13.08.2018: https://www.nasa.gov/content/what-is-nasa-s-asteroid-

Consensys who acquired Planetary Resources in 2018 (founded in 2010 by Peter Diamandis and counting Eric Schmidt and Richard Branson among its investors) and later unlocked the IP to the open-source community[750]. Both examples aim to exploit raw materials, essentially metals and elements in which some asteroids are rich (iron and associated metals, iridium and platinum series, etc.) and to process them to a greater or lesser extent. Moreover, Jeff Bezos believes that humans have to use space resources to protect Earth, as human population has become now big enough to hurt it, as well as to avoid rationing for terrestrial resources in the long run[751]. With his company Blue Origin working on reusable rockets and on a lunar lander, he wants to leverage the possibility that heavy industry move off the Earth[752]. Still both space resource exploitation and space colonisation are very high-risk investments (Toivonen 2020b)[753].

Space colonisation is seriously questionable and controversial for most people as something to be relegated to the rank of pure science fiction (Toivonen 2020b)[754]. With the emergence of New Space age, the projects for developing extraterrestrial life far beyond Earth orbit should no longer be considered as sprouting from the ultimate Sci-Fi imagination.

Over the years there have been various proposals and designs for future space settlements. Based on this observation of backing-up Earth, space activists, such as the Space Frontier Foundation (SFF) in the US, have been vigorously promoting the privatisation of space for a while (Tumlinson 2003)[755]. Much before SpaceX and SFF projects, scenario of space settlement (O'Neill 1976) first envisioned space colonies housing a minimum of ten thousand residents extending subsequently their habitats exponentially through in-situ resource utilisation (e.g. mining and refining of the planet resources) and based on a solar-fuelled and clean manufacturing capacity. The design of such orbital space station town would be circular, and it would spin to simulate gravity. In 1977, NASA published a guide, Space

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redirect-mission (last retrieved on 13.09.2021).

[750] Unlocking Planetary Resources' Intellectual Property on Consensy website: https://www.consensys.space/pr (last retrieved on 13.09.2021).

[751] Dave Mosher and Dana Varinsky, 'Jeff Bezos unveils a giant lunar lander that he says is 'going to the moon' and will help Blue Origin populate space', published on 09.05.2019 by Business Insider: https://www.businessinsider.com/jeff-bezos-blue-origin-moon-lunar-lander-2019-5?r=US&IR=T (last retrieved on 24.08.2021)

[752] Julie Bort, 'Jeff Bezos explains why he's trying to colonize the moon: 'We need to go to the moon to save the Earth'.', published on 07.06.2019 by Business Insider: https://www.businessinsider.nl/amazon-ceo-jeff-bezos-colonize-moon-2019-6/?international=true&r=US (last retrieved on 24.08.2021)

[753] Toivonen (2020b, §3): 'One of the main limitations to the establishment of space colonies and space resource exploitation has so far been that they are very high-risk investments, as they have never been done before. As the timescale for building new space colonies can be considered a long one, anything from the most optimistic vision of 20 years (Elon Musk) up to 100 years (Stephen Hawking), there needs to be long-term planning on global government initiatives and with private corporations providing sufficient funding.'

[754] As pointed out by Toivonen (2020b, §7): 'There are many arguments for and against space colonisation, from Stephen Hawking's view that space flight and the colonisation of space are necessary for the future of humanity as otherwise the human race will become extinct within the next thousand years, to the idea of biosphere survival in the event of natural or human-made planetary-scale disaster, to the availability of additional space resources to enable the expansion of human society. Some concerns have been raised about the enhanced interest and exploitation by organisations that are already powerful, such as military and major economic institutions, which could exacerbate pre-existing detrimental processes such as economic inequality, environmental degradation and even war. In order to ensure human survival, such as in the case of a global catastrophe like a asteroid impact, it would be sensible and advantageous to begin developing space colonies.'

As well as Toivonen (2020b, §7, citing an interviewed panellist's point of view): 'I find space colonies to be neither probable, nor desirable – we have one Earth, with tremendous opportunities, but we are gradually eroding away this in our pursuit for the next big thing, the next growth, the next… something. The dream, or scenario, of creating colonies outside Earth 'in case of' is a lame excuse that is trying to create a utility value for a matter that hasn't got one. (…) For the greater good these 'colonies' would anyhow mean very little. If Earth went through a global catastrophe then there is no place for 7.2 billion people – and no other environment replenishes itself like Earth. It is therefore a 'pie in the sky', literally and figuratively, to wish for space colonies – whilst simultaneously making the Earth that exists in front of our eyes less and less liveable.'

[755] As per Tumlinson testimony (2003) to the US Senate: 'We believe all people (…) will benefit from opening the space frontier. Given the fragility of our planet we also believe that it is vital that we not only preserve the biosphere of earth using the resources of space, but that we expand that biosphere, taking life to worlds now dead. If successful, we see our future as exciting and full of possibility. (…) Finally, and most importantly, we must open the frontier as humans to survive as a species and to protect our precious biosphere from destruction by the forces of the universe or ourselves by making it redundant.'

Settlements: A Design Study (Johnson & Holbrow 1977), to provide a city planning policy guide on what future colonies should look like. It focused on orbital civilian habitats, town-sized space stations housing tens of thousands of civilians each, which follow the real-world laws of physics. It was suggested that the design of the space colonies could be urban, walkable, transit oriented, dense and inclusive, exactly what urbanists advocate for Earth, and which would be physically possible to build if space becomes widely accessible or more heavily settled. A current example of prospective space urban planning such as Nüwa cliff city project is sized for 250'000 people[756].

As a preliminary conclusion on space industrialisation, mankind seeks to reach far beyond the Earth's low orbit and aspires for deep space exploration. In this context, the enormous and fast development of the field of New Space will inexorably push the frontiers of human civilisation towards outer space. From an ecological perspective, such endeavour can be considered as a form of inevitable expansion of the human niche.

As space travel is resource-intensive and polluting, there seems to be a general consensus in the space industry to tackle its environmental impacts. In a broader manner, the community has also started to address further the notion of space sustainability, as introduced in the next section.

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[756] See Nüwa, the first sustainable city on Mars on ABIBOO Studio architecture firm website: https://abiboo.com/projects/nuwa/ (last retrieved on 15.10.2021).

15.4 The current way space sustainability is approached

As we are witnessing an unprecedented expansion of space traffic driven by the New Space movement, the accumulation of space debris, the so-called space junk, is rendering unusable a growing part of the Earth orbit, which could compromise soon safe and persistent human space exploration, exploitation and settlement endeavours.

The flaws in the unsustainable use of space are likely to amplify when thinking of space debris collisions which multiply themselves dangerously over time. Space accessibility may reach its limit sooner than later if no intergovernmental actions are taken. In this respect, Trur (2021) examined the emergence and progress of space debris governance mechanisms. As discussed by Haroun et al. (2021), the presence – and persistence – of orbital debris place man, the Earth, and useful space objects at risk, and is connected to an absence of international regulations.

With such normative context and policy gap, the sustainability facet of space activities has been progressively added to the agenda of space agencies[757] but also of space policy-makers, in particular at the level of international organisations such as the United Nations Committee on the Peaceful Uses of Outer Space (UN COPUOS), essentially at the global level. In 2010, the latter established the Working Group on the Long-Term Sustainability (LTS) of Outer Space Activities, which mandate ended in 2018[758], and that was tasked with producing a set of voluntary guidelines for all space actors to help ensure the long-term sustainability of outer space activities, defined as 'the ability to maintain the conduct of space activities indefinitely into the future in a manner that realises the objectives of equitable access to the benefits of the exploration and use of outer space for peaceful purposes, in order to meet the needs of the present generations while preserving the outer space environment for future generations' (COPUOS 2019). In an earlier report, concerning the space activities and sustainable development on Earth, space technologies were considered to play a key role in the three pillars of sustainable development, as 'they offer valuable tools for supporting sustainable development, the benefits of which are to be leveraged for all humankind. Space-based applications such as Earth observation, global navigation satellite systems, and telecommunications provide objective data and information, which may improve the understanding of trends, assist with the evaluation of needs, and contribute to better-informed decision-making.' (COPUOS 2018). In addition, the report considers that space activities themselves should also 'have minimal negative impact on Earth or the space environment', through technologies that 'minimize the environmental impact of launching space assets and maximize the use of renewable resources and the reusability or repurposing of existing space assets can support these efforts.' The guidelines section D.1 of COPUOS (2019) aims to promote and support research into and the development of ways to support sustainable exploration and use of outer space, including celestial bodies, stating that the conduction of space activities should refer to UN Conference on Sustainable Development (UN General Assembly 2012), and to the social, economic and environmental dimensions of sustainable development on Earth, adding that states and international intergovernmental organisations should take 'appropriate safety measures to protect the Earth and the space environment from harmful contamination, taking advantage of existing measures, practices and guidelines that may apply to those activities, and developing new measures as appropriate' (COPUOS 2019). In the report of COPUOS (2019) to UN General Assembly, the view was also expressed that, while it might not be technically feasible at present to engage in space resources activities, 'space resource-related activities should be based on the principles of sustainable use of natural resources, avoidance of harmful contamination, and efficiency, that appropriate international safety standards should be established and adhered to, and that such activities should be coordinated

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[757] Cf §14.4.1.

[758] United Nations Office for Outer Space Affairs: https://www.unoosa.org/oosa/en/ourwork/topics/long-term-sustainability-of-outer-space-activities.html (last retrieved on 11.10.2021).

at the international level in order to avoid competing interests and minimize conflicts'.

The fast changes happening in the space community are also reflected in the concept of Space 4.0[759], which is characterised by a growing number of public and private space actors, and more and smaller nations involved (Bohlmann & Petrovici 2019). This concept is developed by ESA since 2016[760] to ensure the ongoing success of European space activities, in particular to resolve global challenges and to serve society in the new space era. ESA's proclaimed commitment to UN Sustainable Development Goals[761] also strengthen the role of MELiSSA project and its related Earth-based applications.

Based on the fact that congestion in space is only going to get worse (Holger 2021), ESA is tackling the growing and persistent threat of the space debris removal through its Clean Space initiative[762] and is preparing the ClearSpace-1 mission[763], the first to actively remove an item of debris from orbit and due to be launched in 2025, and led by Swiss start-up, ClearSpace[764].

Through its Global Future Council on Space Technologies, the World Economic Forum developed the 'Space Sustainability Rating' concept[765] to mitigate orbital debris generated by space activities, which will be led and operated by the EPFL Space Center (eSpace).

Lately, ESA also integrated the challenges for circular economy and sustainable living in space and on Earth in their Industry Space Days 2021[766].

As suggested above, the environmental and sustainability considerations of most international space initiatives focus primarily on their benefits for terrestrial sustainability and on the issues of space debris. Next section discusses precisely the relevance to extend the scope of space sustainability to cosmic scale.

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[759] Space 1.0 corresponding to the launch of the first satellites for astronomers, Space 2.0 to the space race from the Cold War to ensure security and prestige, and Space 3.0 representing a period of international cooperation, exemplifyied by the ISS programme: see also the post 'What is Space 4.0' on ESA website:

https://www.esa.int/About_Us/Ministerial_Council_2016/What_is_space_4.0 (last retrieved on 11.10.2021).

[760] Ibid.

[761] ESA and the Sustainable Development Goals:

https://www.esa.int/Enabling_Support/Preparing_for_the_Future/Space_for_Earth/ESA_and_the_Sustainable_Development_Goals (last retrieved on 15.04.2021).

[762] Clean Space initiative on ESA website, 'Clean and eco-friendly space', published on 07.05.2019: https://www.esa.int/Enabling_Support/Preparing_for_the_Future/Discovery_and_Preparation/Clean_and_eco-friendly_space (last retrieved on 05.10.2021).

[763] 'ESA commissions world's first space debris removal', published on ESA website on 09.12.2019: https://www.esa.int/Safety_Security/Clean_Space/ESA_commissions_world_s_first_space_debris_removal (last retrieved on 05.10.2021).

[764] ClearSpace website: https://clearspace.today

[765] Space Sustainability Rating on World Economic Forum website: https://www.weforum.org/projects/space-sustainability-rating (last retrieved on 27.09.2021).

[766] Programme of the ESA Industry Space Days 2021 (07-08.12.2021) availabe on: https://isd.esa.int/programme/ (last retrieved on 01.12.2021).

15.5 Extending space sustainability to cosmic scale

Apart the emergence of New Space field, other main trends of the dynamics of the industrialisation process include the technological acceleration through digitalisation, artificial intelligence and Industry 4.0[767].

Looking at the ongoing fast development of space tourism and satellite-based commercial services driven by New Space, up to the sale of lunar 'real estate', Williamson (2003) suggested that the space environment will become during this century an extension of our current terrestrial business environment[768, 769]. Conceptually, industrial development is indeed expanding, and is not just limited to Earth and its low orbit, so that the limit of terrestrial sustainability has already been crossed up to the spatial brink. At a time when the boundaries of global ecologies and economies extend far below and above Earth's surface, Olson (2018) argued that outer space is not outside the human environment but rather defines it.

As a consequence of the growing importance of space activities (civil and military) on a global scale, the relevant scale for thinking about the evolution of the industrial system is no longer planet Earth, the relevant scale is now the Solar System. Sustainability challenges are on a scale never before seen in human history. As a result of this entanglement of new spatial scales for sustainability, the very notion of sustainability in the context of space development should not focus specifically to near-Earth issues such as space debris, and should rather be envisaged at cosmic scale.

Based on the observation that the world is currently threatened by global challenges such as natural disasters, pandemics, or climate change consequences, which all require global actions, space should become an enabler, as never before, as it 'can play a pivotal role in meeting those challenges' (Lehnert et al. 2017). As an example, Secure World Foundation (SWF), an NGO that envisions the secure, sustainable and peaceful uses of outer space contributing to global stability on Earth, considers space activities and tools as highly relevant for attaining sustainability objectives, by using space environment for national security purposes, Earth observation, telecommunications (including financial transactions, internet, telephone, data transfer, and television), navigation, scientific exploration, or economic development. According to SWF (2018), space sustainability is '[e]nsuring that all humanity can continue to use outer space for peaceful purposes and socioeconomic benefit now and in the long term. This will require international cooperation, discussion, and agreements designed to ensure that outer space is safe, secure, and peaceful.'

In this context, Lenhert et al. (2017) gave an overview on the man-made and natural risks that humankind is facing, risks bearing the potential to end humanity, and describes the way that space can be used as a tool to prevent and manage all these risks. In addition to enabling a deeper understanding of our universe, the authors considered that space activities leverage the use of space as an additional sphere and sector, through which humankind can increase and secure its wealth. They also argued that such activities are game changing in the way humanity's existence can be sustained on Earth, and that,

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[767] Industry 1.0 corresponding to mechanisation, water and steam power, industry to mass production and electrification of the industrial system, 3.0 computer and automation, 4.0 to cyber-physical systems digitalisation based on internet of things and systems. See notably Bernard Marr's article, 'What is Industry 4.0? Here's A Super Easy Explanation For Anyone', published in Forbes magazine on 02.09.2021:

https://www.forbes.com/sites/bernardmarr/2018/09/02/what-is-industry-4-0-heres-a-super-easy-explanation-for-anyone/?sh=356d43c39788 (last retrieved on 22.09.2021)

[768] Williamson (2003, p. 47): 'The exploration of the space environment—by robotic and manned missions—is a natural extension of mankind's desire to explore our own planet. Likewise, the development of the space environment—for industry, commerce and tourism—is a natural extension of our current business and domestic agenda. Unfortunately, this brings with it the ability to pollute, degrade and even destroy aspects of the space environment.'

[769] Toivonen (2020b, §7): 'The desire of the world's powerful countries and companies to exploit the natural resources creates questions not only around the environmental impact on the untouched space environment, but also around creating global equality for those not yet able to access space.'

socioeconomically, they provided a technical backbone for stable and reliable cooperation in the international governance arena, and serve as crucial economic stimulator.

As summarised by Iliopoulos and Esteban (2020), sustainable space exploration is therefore ‘understood as an activity of contentious importance that depending on the author, limits the risk of human extinction, minimizes space pollution or environmental degradation in space (such as space debris) and/or increases the welfare of humanity on Earth (by technological advancements in fields such as medicine or environmental management)’. Nevertheless, as pointed out by Toivonen (2020a), public-private partnerships in the space sector have previously tended to be economy-based, with environmental aspects regarded as voluntary.

Nevertheless, human space exploration can amplify some of the negative impacts exerted by our modern society on Earth. Nowadays, the environmental impact of space industry is rather limited due to the still relatively small number of launches and regular flights, even if they I are increasing year after year. Nonetheless, space exploration strains upon our available resources on Earth as well. Magnified by the perceived image of space tourism, the New Space industry, in this time of climate change, will increasingly be associated with growing environmental impact and the generation of more space debris[770]. Indeed, space travellers per capita contribution to climate change is among the highest of any human activity, especially in terms of greenhouse gas emissions, considering the whole life-cycle and short duration of their flight or stay.

With a planned increased of launches rate, Global business organisations such as World Economic Forum seized the questions of the consequences on the climate of space activities[771]. Faced to the above impacts, scientists are calling on policy-makers to react, so that polluting emissions from spacecraft engines become regulated at international level. Moreover, an executive member of the SWF estimates that human spaceflight emissions are as obscure to us at present as space debris pollution was in the 1970s, and that we don’t know how to quantify the rocket emissions impact[772]. In any case, rocket launch consumes a considerable amount of energy, even for suborbital flights. For instance, based on the SpaceShip Two environmental assessment report, each Virgin Galactic suborbital flight would emit a total of 27 tonnes of CO_2 to carry eight people (including two pilots)(Federal Aviation Administration 2012)[773]. This corresponds to 4.5 tons of CO_2 per space tourist seat, a massive amount for a few minutes’ flight that is more than twice than the yearly CO_2 budget per capita from Paris Agreement set out to limit global warming to 1.5°C above preindustrial levels (Intergovernmental Panel on Climate Change 2018). By comparison, Blue Origin flights are significantly cleaner as their emissions are mainly water and some minor combustion products, and nearly no CO_2 by consuming a mix of liquid hydrogen and liquid oxygen[774, 775], even if water vapour in the upper atmospheric layer induces a

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[770] Toivonen (2020b, §7): ‘[W]ith a limited display of attention paid to ecological and ethical considerations, even those who could afford a trip may pass up the experience to avoid potentially being shamed, instead of admired for their bravery, and this would certainly not be economically sustainable for the industry in the long run. The future of the space tourism industry is dependent on how the public views its value as it begins fully operating – the options are that it could remain nothing more than a dinner party topic for a small, elite group, or alternatively, perhaps only the universe will be our limit.’

[771] John Letzing, ‘How many space launches does it take to have a serious climate impact?’, published on World Economic Forum website on 23.07.2021: https://www.weforum.org/agenda/2021/07/what-s-the-climate-impact-of-space-exploration/ (last retrieved on 05.10.2021).

[772] Corbin Hiar, ‘Countdown to billionaire space race raises climate questions’, published on E&E News on 09.07.2021: https://www.eenews.net/articles/countdown-to-billionaire-space-race-raises-climate-questions/ (last retrieved on 20.09.2021).

‘With rocket emissions, we are now where the community was regarding the space debris issue in the 1970s’, said Peter Martinez, the executive director of the Secure World Foundation, a nonprofit focused on the sustainable use of space. Space debris is defined as defunct human-made objects floating above Earth, such as broken satellites, abandoned rockets or fragments of earlier spaceships. ‘We don’t quite know how to quantify it,’ he said, referring to rocket emission impacts.

[773] As per Exhibit 4-5 of the report.

[774] See Blue origin B-7 engine specifications: https://www.blueorigin.com/engines/ (last retrieved on 05.10.2021).

[775] George Heynes, ‘Liquid hydrogen blasts Jeff Bezos’ New Shepard into space with low carbon emissions’ published on H2-view.com on 21.07.2021: https://www.h2-view.com/story/liquid-hydrogen-blasts-jeff-bezos-new-shepard-into-space-with-no-

greenhouse effect as well.

NASA documented the ecological effects of the 135 launches of the US Space Shuttle Program on regional ecosystems of east-central Florida around the John F. Kennedy Space Center (Hall et al. 2014). The monitoring covered particularly the effects of the water-based sound suppression system, the noise pollution in the vicinity of the launch pads and the impact of the ground cloud generated at launch, which caused particle exhaust product near-field deposition (e.g. Al, Cu, Fe, Mn, as well as HCl). NASA reported positive and negative ecological trend over the 40-year life cycle of the shuttle programme for the air quality, soil, water, wildlife of the surrounding ecosystems of the launch pad. In the report, the agency notably argues that the shuttle programme was conducted mainly in already developed facilities and industrial areas and conclude that the launch and operations impacts were minimal as a result of the low launch rate. One can argue that this clearly does not mean that they were not impactful per se, but simply that as they were spread over time, their effect was diluted.

In a detailed study, Dallas et al. (2020) reviewed the environmental impacts of space launches, specifically of rocket propellant emissions. Their findings are that the depletion of stratospheric ozone is the most immediate concern and the need for further study of the cumulative impacts that frequent space launches have on climate change, ecosystems and human toxicity before the number of launches greatly increases.

Space vehicle launches produced a ground cloud, and later an exhaust cloud, typically composed of H_2O, CO_2, Al_2O_3, NOx, HCl and soot as major constituents. These main emission products and vapours have broad range of environmental and health impacts. For instance, acid rain causes acidification of the soil system and acid burns on the vegetation leaves. Other research studies are pointing out that the combustion products injected into the stratosphere are playing a role of climate modifying agent (Ross & Vedda 2018). As an example, combustion products can play a role of an umbrella that is cooling the Earth's surface, as the accumulation in the stratosphere of alumina oxide and black carbon particles (soot) are thought to be respectively reflecting part of the sunlight, and warming the surrounding stratosphere. In addition these particles are depleting the ozone layer. Rocket fuels should not use chlorine (ammonium perchlorate being used an oxidiser) as it also participates to ozone depletion. In addition, the ecotoxicity of the remaining fuel should be considered and mitigated.

ESA estimates that between 100 and 200 tons of human-made hardware re-enters Earth's atmosphere every year in an uncontrolled fashion (Holger 2021). Therefore, re-entering orbital debris should be more studied, as the vaporisation of space junk hardware falling back into the sky generates smoke particles that can affect the global atmosphere[776].

The reusability of the rockets is both beneficial from the environmental and economic standpoints. Nonetheless, even the reusability of the Falcon 9 implies its recovery after landing on the sea by specialised ships, with still massive CO_2 emissions as a result (Federal Aviation Administration 2020)[777].

Acknowledging the above, the antagonism between space exploration and sustainability need to be overcome and, as for space tourism (Fawkes 2007), space exploration should therefore be systematically addressing sustainability, should it be on the operational (environmental impact minimisation through IE), cultural (for inspirational, educational, pedagogical purposes), economic (CE approach implementation), or resource (use sustainable rocket fuels or ISRU strategy) levels.

In conclusion, the current human predicament implies to integrate sustainability at any scale on Earth,

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carbon-emissions/ (last retrieved on 05.10.2021).

[776] David Leonard, 'How Much Air Pollution Is Produced by Rockets?' published in Scientific American on 29.11.2017: https://www.scientificamerican.com/article/how-much-air-pollution-is-produced-by-rockets/

[777] As per §4.4.1.3 Dragon Recovery (Federal Aviation Administration 2020): 'Emissions were estimated for total carbon dioxide equivalents (CO2e) for annual operations, at 3'815 metric tons CO2e from six Dragon landings'.

in near orbit and beyond. Space sustainability should become one of the key focus of space exploration, but which could only be achieved by engaging space agency, New Space industry, international governmental and regulatory organisations.

In its final section, the chapter discusses the contributions of ACE development to space sustainability.

15.6 Contributions of ACE development to space sustainability

As a result of evolution, man is not made to live in outer space or on another planet. Long duration travel or stay in the hostile space environment has been proven to have a negative impact on the human body, with medical issues for astronauts caused by microgravity (weightlessness) and radiation exposure. In this context, ACE are key to provide acceptable and sustainable conditions for extraterrestrial life. First, the main challenges of human space exploration consist in establishing a deep understanding of how the human body and psychology are affected in the long run by the space conditions (gravity, pressure, radiation, confinement, etc.) as well as finding protection schemes or countermeasures to reduce the health risks for long-term space travellers up to space settlements. In particular, design and validation of life support units (nutrition, oxygen, energy, recycling, medicine, etc.) are crucial, as extensively discussed in the previous chapters[778].

The ambition to one day walk on the surface of another planet in the solar system – or even colonise it – depends on the development and operation of ACE in the form of ALSS, which are absolutely essential for the successful establishment of a Martian base.

If space ACE are required for the technological empowerment for long duration manned space missions, and despite the current bubbling with excitement around deep space exploration, SpaceX do not say a word about how people will survive once they get to Mars (Mosher 2017). So it appears – at least today – not to be part of their capabilities or current development roadmap. Therefore, it is expected that third-party stakeholders, and most probably space agencies, potentially through international cooperation, as well as private stakeholders, shall provide space ACE/ALSS capacity to make such endeavours possible. By comparison, ACE developers ambition seems modest with missions usually based on a limited crew of 2 to 6 people. In any case, an entire industrial base would have to be created on the planet to colonise, for instance for the Earth-to-Mars business, knowing that mining resources and refining all of the different materials would be feasible only by dealing with much more difficult environment than Earth.

In definitive, ACE development is about creating and manipulating a downsized synthetic biosphere that could ultimately be extended and allow human settlement on other celestial bodies. In the perspective of space industrialisation at the scale of the Solar System, the associated cosmic industrial ecosystems will therefore have to be much more important and certainly more complex – notably due to their size – than those planned for the first scientific exploration missions with a human crew. Even with the ongoing interest for developing a Moon village (ESA 2020)[779], it seems essential to validate the Mars case before sustaining life anywhere in the solar system.

Some of the first considerations for envisaging the notion of sustainability (in the human life perspective) at cosmic scale are summarised in the following paragraphs.

One big vision would be to integrate the sustainability perspective at all spatiotemporal levels of any space ventures in order to guarantee that the trend for New Space develop a strong sustainability mindset with concrete actions and returns. Therefore, future space ACE development needs to consider environmental impacts and apply CE concept and sustainability practises to itself. In particular, the sustainability aspect of space exploration should not be idealised and should take into account the effective environmental cost of the full life-cycle of the mission. Consequently, sustainability approach should obviously encompass all operations and localisation of the mission preparation from the ground simulator to the space vehicle, via the spaceport, the space suits, etc.

Marboe (2019) analysed the ethical and legal principles governing human space activities such as those

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[778] Cf §4.2.2 and §13.3.2.

[779] Cf §4.1.

applicable to a Moon village. He pointed out that the ethics of human beings living together depends on shared values and principles that are ‘reflected in legal rules and regulatory frameworks to provide them safety, security and foreseeability’. In the context of CH in space, it is hereby proposed that such regulatory frameworks, still in their infancy, should be further developed and extended to the entire scope of future human outer space activities and that it should include space sustainability as an essential aspect. In his essay on rules in space, Kovic (2018) argued that we urgently need a legal framework for space colonisation[780], and that such governance should be a global priority even today, before colonisation is technologically viable. The true sustainability of space colonies depends on the emergence of clear rules and laws, potentially independent from terrestrial ones[781]. Later, future successful space colonies ‘will need to be independent and self-sustainable habitats, not mere colonial outposts controlled from Earth’ (Kovic 2018).

Sustainability should be reconceptualised, especially its relationship with cosmic scale as a new frontier. A specific framework for sustainability at the cosmic-wide level should be elaborated, for instance following the same approach used for the standard on closed habitat described earlier[782]. Such referential on space sustainability should go beyond space debris management and mitigation, or Earth observation, remote sensing and environmental monitoring. It should particularly approach all the aspects of the sustainable use of space, not only environmental, technological and economic, but as well as legal, regulatory and societal dimensions.

A starting point could be to apply the ecorestructuration of the industrial system[783] to New Space-driven sustainable space exploration. As a reminder, the four main scopes ecorestructuration cover material flow circularisation, losses minimisation, dematerialisation and decarbonation. They are briefly discussed below and completed with the topics of sustainable resources management, interstellar dimension for human spaceflight, robotisation and self-reproducing factories, digitalisation and space, and finally life reproducibility in space.

Circularisation by closing material loops

Circularisation is the very purpose of ACE and starts at the scale of self-sufficient space habitat. As bio-cybernetic LSS and in the IE perspective, ACE can be used as a framework and laboratory to test concept and practical approaches to sustainability[784] both at the scales of a mesocosm[785] and a minimal habitat[786].

The space habitats constraints discussed earlier[787] include reliability, logistics, size and performance. Particularly, the reduction of the onboard mass of metabolic consumables necessary for the survival of the crew aims at making the ACE operating in a sustainable way, notably through space ACE-driven

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[780] As mentioned in Kovic (2018): ‘Surely there are laws and institutions that regulate what can and cannot happen during space colonisation? Surely uncertainty, lawlessness and chaos in the matter of expansion and colonisation are spectres of the past, not the modus operandi of our future expansion into space? The answer is no. There is no meaningful space-colonisation governance framework to speak of. As of now, in 2018, space colonisation is a veritable free-for-all. And this absence of a forward-looking space-colonisation governance framework could have disastrous consequences.’

An anonymous comment to this essay included the following: Until the transportation stream is highly efficient and financially feasible, the populations on the moon and Mars will be very small, on the order of towns. Towns will be run according to project management, not laws. The rare individual who causes trouble while on the moon or Mars will be fired, and shipped back to Earth. No laws needed.

[781] The Outer Space Treaty stipulates that the jurisdiction of any spacecraft and any of its personnel, is the jurisdiction of the spacecraft’s and/or the personnel’s country of origin.

[782] Cf §Annex H.

[783] Cf §3.8.1 and Annex A-§7.2.2.

[784] Cf §5.3 and §6.1.2.

[785] Cf §3.1.

[786] Cf §13.4.

[787] Cf §4.2.2.

systematic resource valorisation. Therefore, making space travel more feasible is about realising how resource constraints limit space travel. Consequently, these constraints foster sustainability not only technically and logistically, but also economically.

As a reminder, when it comes to focusing on the sustainability of ACE, it is not only necessary to carry out a careful control and monitoring of their environmental conditions and exposome[788], but also to be able to finely regulate homoeostasis in case of drift, as early as possible. For operating the ACE in a sustainable manner and ensuring human occupants survival, circular systems have to be set up in order to correct, block, or replace automatically any process that would diverge from its optimum or suddenly fail down.

Oïkosmos programme highlighted the noticeable similarities between the ecological challenges we are facing both in space and on Earth[789]. Calvert (2013) argued for the increased involvement of the social sciences and humanities for dealing with the grand challenges which galvanise research efforts. In this perspective, the present dissertation notably explored how ACE research can facilitate to meet the sustainable development-related grand challenges of global warming, ecotoxicology, ecosanitation or sustainable resource management, to cite just a few, that all benefit an interdisciplinary and integrative approach. In particular, space ACE development can contribute to terrestrial sustainability through Earth-based applications[790] and the operationalisation of IE and CE approaches[791]. Nonetheless, the benefits for terrestrial sustainability due to the ability of ACE to manage limited resources should not be sufficient to consider manned space exploration as a topic of utmost importance. Indeed, acknowledging the positive impact of space ACE to terrestrial sustainability[792], the interest in space of private stakeholders still deeply questions circularity. To take an example, the flip side of mining asteroids, satellites, or other planets of the solar system is that it reproduces the current linear extraction approach that is depleting our resources.

As the usage of resources in space habitat has to be extremely prudent, the valuation of resources is bigger. Space habitats thus imply an intense use of resources for the immediate built environment of spacefarers. If space tourism has to create a feeling of 'value for money' for its customers (Toivonen 2020b), instead space exploration implies to generate 'value for resource', 'value for Earth' ,'value for science' and 'value for humankind' to its promoters and financers.

At a much larger scale compared to habitat level, sustainability also encompasses the immense surrounding environment of the solar system at cosmic scale.

Sustainable resources management at cosmic-wide scale

One critical question is what settling in space means for sustainable resources management on Earth and in space. Information from Earth observation satellites is instrumental for defining ways to optimise the use of natural resources. Current and future space technologies are much helpful for improving the sustainable use of natural resources, monitoring and contributions to mitigate climate change (including for natural disasters prevention), and improving connectivity in remote areas. The same logic should apply for the sustainable management of space resources at cosmic-wide scale in order that deep space exploration goes beyond a pure exploitation. In this respect, an inventory of the resources of the Solar System should be made at a sufficiently early point in time in order to know just what lies out there (Elvis & Milligan 2019). The early phase of deep space conquest should not result in the intensive and

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[788] Cf §5.3.

[789] Cf §6.1.2 and §13.4.

[790] Cf §14.2.

[791] Cf §14.4.

[792] Cf §14.

shameless exploitation of other planets, at least in its early phase. With the aim to start a forward-looking planning of Solar System-wide ‘nature reserves’, Elvis and Milligan (2019) questioned how much of the Solar System should be reserved as wilderness, off-limits to human development. They estimated that available space resource utilisation should be limited to one eighth, with the remainder set aside, as reaching the point of exhaustion is associated with exponential growth, giving us at least 3 doubling times as leeway, as it may be far easier to implement in-principle restrictions at an early stage, rather than later. Otherwise, the authors foresaw that a super-exploitation might be effective, at least at the level of a few resources[793]. According to them, space may, in fact, be the only place where a more demanding conception of wilderness as ‘pristine environment’ is now viable. Nonetheless, by the end of the present century, both the lunar and Martian surfaces as a whole are likely to be somewhat affected by sustained human presence, with expected dissipations of contaminations through Martian wind for instance.

Starting from an almost blank page, human-driven space resource use and distribution needs critical consideration at sociological level. According to Bluth (1979), human space exploration offers to humanity a novel and unique opportunity to ‘maximize behavioral systems that significantly improve the quality of life’. Consequently, at the sociological level, ‘space development represents an unprecedented new start, a vast opportunity for fresh beginnings.’ In a sense, the approach from a scientific and technological programme such as Oïkosmos could be applied at the level of a small society.

Losses minimisation

The challenge to reduce as much as possible the amount of waste left behind by spacefarer. Uncontrolled development of New Space would damage both Earth-bound and celestial environments. Cohen (2017) also pointed out the subversion of ‘adventure’ in space tourism, the banalisation of the sublimity of the space experience, and the suppression of the pristinity of other celestial bodies by space use development.

Early settlers will have to bring everything to Mars to ensure earthless habitability. On a vessel in-route to Mars, there will simply be no available resources to replace the lost breathable or consumable resource. The destination may literally not have the resource available (Häuplik-Meusburger & Bishop 2021).

As for the vast majority of the times, ISRU is only available for specific resources, space activity usually deals with resources scarcity and does not tolerate to squander resources. Whereas the availability of Earth-bound resources is often a matter of accessibility, habitability for extraterrestrial locations must be approached not only from the viewpoint of scarcity but one of finiteness (Häuplik-Meusburger & Bishop 2021).

For space ACE development, Walker and Granjou (2017) concluded that ‘[t]he futures anticipated by MELiSSA emerge out of a complex lineage of encounters between colonisation and sustainability, endlessness and scarcity of space and resources, purity and contamination.’ Elaborating on the further aspects, approaching an ethic of human space exploration and settlement, Cockell and Horneck (2004) warned that human exploration and settlement on Mars would have ‘environmental impact (…) in the form of contamination with micro-organisms and spacecraft parts’. Regarding the latter point, a particular

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[793] Elvis and Milligan (2019), p. 580: ‘To summarize, while we remain dependent upon the resources present inside the Solar System, and while economic growth remains exponential, we should regard, at most, one-eighth of the Solar System as humanity’s to use. (…) If unchecked, such growth will tend towards a point of super-exploitation (…). On a timescale of less than a millennium we could have super-exploitation of the entire Solar System out to its most distant edges. A millennium is a long time to look forward, but is not long in human history, and is tiny in Solar System history. Facing up to this worrying consequence of economic growth involves accepting that a circular economy with extensive recycling of raw materials is ultimately a requirement. If we can begin on a mere planetary scale now, we will be prepared to adapt to a Solar System scale as we gain that capability.’

attention should be paid on the planetary protection of all visited solar system bodies, even for uncrewed missions[794]. If (microbial) cross-contamination is almost impossible to prevent, there should be international treaties, such as Outer Space Treaty[795] (United Nations 1967), putting sustainable resource management and responsible in-situ resource utilisation as a commitment for any future human space exploration beyond low Earth orbit. The concept of Martian 'planetary parks' proposed by Cockell and Horneck (2004) set out the following restrictions (p. 294): no spacecraft/vehicle parts to be left within the park; no landing of unmanned spacecraft within the park; no waste to be left within the park; access only by foot or surface vehicle along predefined routes or landing by rocket vehicle in predefined landing areas; and all suits, vehicles and other machines used in the park to be sterilised on their external surfaces to prevent microbial shedding.

In any case, if ACE are mandatory for any foreseen space colonisation, their further-reaching development should not be confused with 'terraforming' (Zubrin & McKay 1997) of a planet such as Mars, the Moon, or other bodies by deliberately modifying progressively through geoengineering its atmosphere, temperature, or ecology to be similar to those of Earth in order to make it habitable by humans.

Dematerialisation

Alternative and less Earth-harmful methods of launching spacecraft to orbit and beyond are being developed. A disruptive example is SpinLaunch's vacuum-sealed centrifuge[796] which can accelerate a rocket to more than 8'000 kilometres per hour. The tether-based spinning launch system is using kinetic energy as the capacity to get off the ground about 100 kilograms of payload to orbit, equivalent to a several microsatellites, with first test flight of a prototype in New Mexico in late 2021[797]. Companies such as Astra Space and[798] Rocket Lab[799] are offering new launch services for payloads up to 500 kg to 500 km low Earth orbit, based on micro rockets. Such solutions enable repeated and industrialised sendings which provides advantages in terms of cost reduction, risk reduction, automation. In the context of human space travel, such methods would send in orbit structures, equipment, and supplies for in-space infrastructure assembly with the least environmental impact possible. With a ground factory that would send payloads from Earth in a quasi-continuous mode, one could imagine sending the original elements of a biosphere with AI managing the reception and assembly.

Decarbonation

Development of alternative and more sustainable fuels, such as synthetic and carbon neutral fuels produced from solar energy, water and renewable carbon sources[800], could decrease the environmental impact of rockets indirectly, but even more importantly, their whole production pipeline should be

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[794] Indeed, as highlighted by Toivonen (2020b, §7): '[T]he first colony from Earth may already exist on the surface of Mars, in the form of bacterium, as in the early days of space exploration the probes were not properly disinfected.'

[795] The Outer Space Treatee is the seminal multilateral treaty concluded in the Cold War era that set out the general legal principle applicable to space activities

Hertzfeld (2009) and Bohlmann & Petrovici (2019) provide a general overview of the public international law governing the exploration and use of outer space.

[796] Daniel Oberhaus, 'Inside SpinLaunch, the Space Industry's Best Kept Secret', published on Wired magazine on 29.01.2021: https://www.wired.com/story/inside-spinlaunch-the-space-industrys-best-kept-secret/ (last retrieved on 10.11.2021).

[797] Elizabeth Howell, 'Startup SpinLaunch completes first test flight with wild rocket-flinging launch system' published in space.com on 10.11.2021: https://www.space.com/spinlaunch-first-test-flight-success (last retrieved on 10.11.2021).

[798] Astra website: https://astra.com (last retrieved on 01.12.2021).

[799] Rocket Lab website: https://www.rocketlabusa.com (last retrieved on 01.12.2021).

[800] Rami Mandow, 'Renewable Rocket Fuels – Going Green and Into Space', published on Spaceaustralia.com website: https://spaceaustralia.com/feature/renewable-rocket-fuels-going-green-and-space (last retrieved on 20.10.2021).

focusing on carbon neutrality. Mars colonisation demands technological advances to enable spacefarers return to Earth, notably provided by a biotechnology-enabled ISRU strategy, based on photosynthetic cyanobacteria (*Arthrospira plathensis*) conversion of Martian CO_2 into sugars that are upgraded by engineered microbes (*Escherichia coli*) into a Mars-specific rocket propellant (Kruyer et al. 2021).

In any case, decarbonation is not necessary in a Martian context. Composing 95% of the Red planet atmosphere, carbon dioxide is on the contrary a valuable resource for ACE development. On Mars, semi-closed habitats with a capacity to use resources in situ (e.g. semi-closed artificial ecosystem, with external CO_2 supply[801]) seem more appreciable than any terraforming initiative, in order to extend the life of the ACE and to extend the planetary base with bigger or new ALSS features.

Ellery (2020) discussed a sustainable closed loop lunar IE system. In particular, if water and oxygen are abundant resources on the Moon, lunar ISRU and extraction potential is limited for C, N, P, S and K and thus for food production (Ellery 2021). In this latter paper, a sustainable extraterrestrial settlement can only be envisioned if it maximises exploitation of energy sources and minimise consumption of non-renewable energy sources; minimise the generation of toxic by-products; develop industrial ecosystems of interlocking processes that feed waste of one process into another; and exploit feedback loops to recycle scarce resources.

Interstellar dimension for human spaceflight

Sustainability debates are inseparably connected to considerations on space and time. The limitations on human cosmic expansion result from the huge distances for space travel beyond the solar system, doubled by the astronomic cost of such trip (Cohen 2017). Journey times for interstellar distances would last centuries for anything but microscopic masses (Elvis & Milligan 2019) as targeted by initiatives such as Breakthrough Starshot project[802] or NASA Starlight program (Lantin et al. 2022), the latter targeting to send radiation-tolerant microbial life outside of the solar system. Manned interstellar journey would necessitate the construction of an 'artificial mobile world-like environment for the sustainable support of a town- to city-sized community of travellers', with as a consequence 'a shift in the dominant mode of human civilisation from planetary to space-based life' (Ashworth 2012, p140). Volponi and Lasseur (2020) discussed the monumental challenge of exploring the universe outside the Solar System, notably based on the planned extensions and upgrades of existing space ALSS capabilities. With the closest star Proxima Centaury at over four light years from the solar system, envisaging interstellar travel implies travel times longer than human life. Some of the few solutions available to rely on multi-year hibernation (Choukèr et al. 2019) or more plausibly multigeneration ships. Designing such interstellar vessel for human migration to exoplanets requires establishing the starship population with an estimation range from 14'000 to 44'000 people to be genetically viable (Smith 2014), with population changes following demography patterns occurring as on Earth (e.g. in terms of birth and mortality rates). As stated by Volponi and Lasseur (2020), such gigantic spaceships has to be a 'mini replication of Earth not only from the ecological point of view, but also from the physical and social structures' and shall function as a 'miniature Earth', with 3D printing and nanotechnology capacity for technical item production or repair.

In addition, if humanity would develop and settle in space, attempts to make its body more suitable to space habitation would be expected, for instance through genetic engineering or even technical implants to make the body become bionic, as a form of transhumanism upgrade (Gallego 2016).

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[801] Cf §4.3 and Annex A-§7.4.3.4.

[802] Financed by Facebook founder Mark Zuckerberg, the Breakthrough Starshot project aims to demonstrate proof of concept for ultra light-driven nanocrafts, pushed by a ground-based light beamer – miniature space probes attached to lightsails – to speeds of up to 150 million kilometers per hour, laying the foundations for a first launch to Alpha Centauri. Along the way, it is expected that the project can benefit to astronomy, notably for solar system exploration and detection of Earth-crossing asteroids: https://breakthroughinitiatives.org/initiative/3 (last retrieved on 15.09.2021).

Robotisation and self-reproducing factories

Sustainability should be approached even for non-crewed missions. The use of robotics has many scientific advantages for investigating Mars soil without a limited mission duration, the high cost of life support and the return transportation involved in manned missions.

At the system level, the coming in the relatively near future, of self-reproducing real physical devices would be a radical revolution. This way, as mentioned by Erkman (2004), the industrial system, seen as an evolutionary outgrowth of the biosphere and by analogy between blueprints and genes, would acquire one of the fundamental properties of living matter. In the ACE and CH contexts the fascinating and ultimate questions of self-reproducing robots (Zykov et al. 2005; Suthakorn et al. 2002) and self-reproducing lunar factories (Freitas & Zachary 1981) have been addressed, some of them for decades (Figure 52).

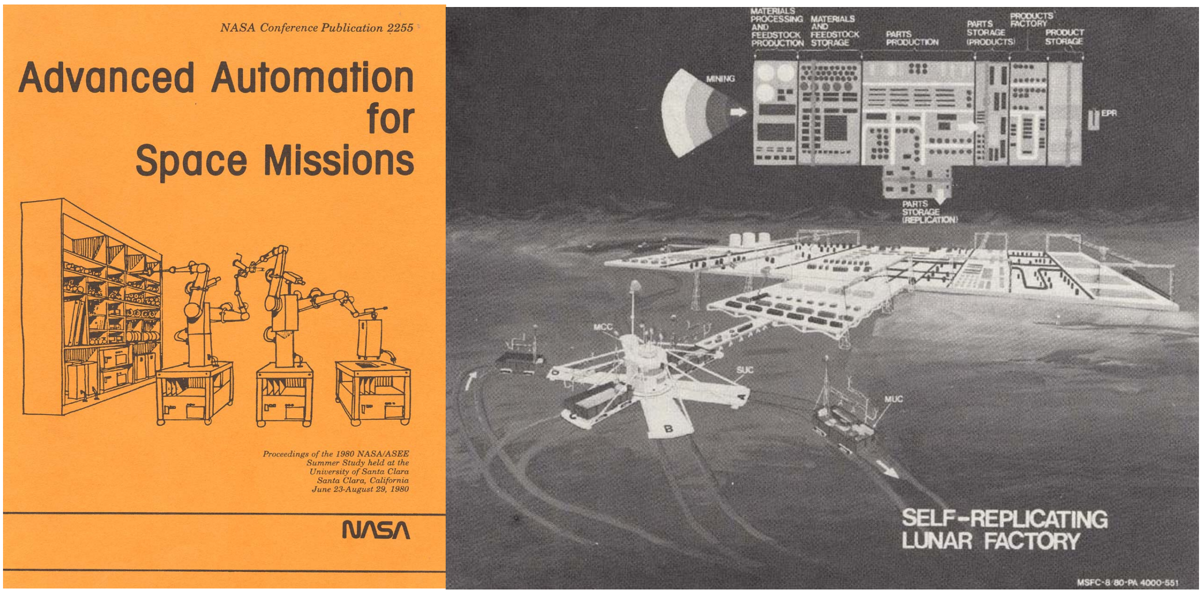

Figure 52: Self-reproducing lunar factories
Self-reproducing lunar factories have been conceptualised for decades. Source: Advanced Automation for Space Missions (NASA 1980).

Digitalisation and space

ACE contributions should be connected to the current all-encompassing economic development, from CE to digitalisation.

As discussed earlier[803], the closer link between space ALSS activities and ICT (e.g. data analytics, big data, cloud computing) is also raising new strategic issues on the critical technologies and capacities. Digitalisation fosters the development of New Space, through recent technical progress in miniaturisation and robotics (e.g. for food production apparatus) and 3D printing for smart habitat construction, and to cite just a few. As an example, AI SpaceFactory designed a 3D-printed space habitat analogue, using innovative and ISRU-based construction materials, from a mixture of basalt fibre extracted from Martian rock and renewable bioplastic processed from plants grown on Mars[804].

Combined together, the related enabling technologies will support the automatisation of most of ACE

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[803] Cf §5, Annex A-Part II, §14.4 and §15.5.

[804] See Marsha space habitat on AI SpaceFactory website: https://www.aispacefactory.com/marsha (last retrieved on 15.10.2021).

space applications. The pinnacle of this technology roadmap should be realised through artificial intelligence, which algorithms leveraging ALSS systems as ultimate game changers for long-term space exploration. Indeed, at some point of technological development, potentially only in a few decades, machines with artificial intelligence might implement such exploration and settlement for ensuring their own silicon-based development. Even though lots of challenges would remain, it would have the strong advantages to include lifelike technologies developed with much fewer elements from the periodic table to take away, compared to what humans would need for an extra-terrestrial biosphere based mainly on living organisms.

Consequently, with the technologisation and digitalisation processes taking place, ACE-based manned space exploration missions might rely less on their biological components and be more silicon-based in the next decades, and more aligned to Thorpe's (Thorpe 2016) argument that 'the trajectory of capitalist technology is toward artificial life on a dead planet'. Such artificial life could be leveraged by a silicon-based ACE roadmap, ultimately made possible with the convergence of the ACE development with synthetic biology, artificial intelligence and robotics.

In a shorter-term perspective, digitalisation will facilitate crewed missions but has also the potential to replace some of them in the future, by combining virtual reality (VR), artificial intelligence and algorithms within an all-pervasive VR universe like the metaverse (Sparkes 2021; Stokel-Walker 2021).

Life reproducibility in space

ACE projects embolden what is often seen as a utopia, by evoking the possibility that some happy few humans can escape whatever would happen to their Mother Earth and anticipate that life can continue and be spread elsewhere in the cosmos. Despite the fact that we are not there yet for space ACE in the perspective of exobiology, we can already forecast that quasi-closed systems are already in the medium-term outlook, and are not a phantasmagoria.

ACE development shall provide crucial lessons about how to maintain life in a distant future in a space environment somewhere in the Solar System, with the first permanent settlements being most likely located on the Moon or Mars, and even later on large-scale space stations such as artificial planet (Glover 2013). Among the perspectives that support space colonisation (Toivonen 2020)[805], one can consider the first colony as the initiation of humanity self-replication process in space.

The way space exploration offshoots can revitalise human societies is expressed in the idea that 'the Earth is not sick: she's pregnant' quoted by Collins and Autino (Collins & Autino 2010). Such analogy suggests that it is not about mankind leaving Earth but more about (human) life perpetuating itself at cosmic scale. In such type of space exploration and in the perspective of exobiology, humans will inevitably take on other organisms: ACE organisms, their own commensal flora, and most probably a full set of microbial spores – as space hardware cannot be totally sterilised before launch – which all have the capacity to reproduce in space habitat.

In the future, as above-demonstrated, outer space evolution may play a central role in determining the long-term sustainable evolution of humankind and the viability of our species (Spector et al. 2017). As

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[805] Toivonen (Toivonen 2020), based on McKnight (McKnight 2003): 'Perspectives that support space colonisation: the first colony could be counted as the Earth's first act of self-replication, enabling space manufacturing and allowing a further increase in colonies, while eliminating costs and dependence on Earth; It would satisfy the human drive to explore and discover; There is no known life in space, meaning no indigenous habitat suffering from human colonisation; Overpopulation of the Earth needs new solutions to replace non-renewable resources; If Earth's resources are replaced with those from space, in theory the Earth's population may no longer need growth limitations; The Earth's environment can be spared by moving some industry and also human inhabitants to space colonies; It would ensure the survival of Homo sapiens if the Earth became uninhabitable in the case of a sudden catastrophe such as an asteroid impact.'

a form of inevitable expansion of the human niche[806], this evolution could lead in the long run to a speciation process in space. For the space enthusiasts, opening the last high frontier of our knowledge is almost a human necessity and a prelude for expanding life throughout the universe by making part of our biosphere redundant, and to back it up (Tumlinson 2003). In such biospheric perspective Margulis (1999) discussed the replicability of a miniature Gaia[807], whose notion was introduced earlier[808]. On the other hand, the self-sufficiency provided by the life support units of a CH[809], is a key factor for perpetuating its ACE sustainably, and especially for enabling the reproductivity of its organisms, including its human occupants. Therefore, there is a clear parallel between this burgeoning of Gaia for space exploration and the very purpose of ACE development, and such portable ecosystems seem to represent one of the few possible solutions to spread reproducible life within the solar system, reproductivity being in the end one of the very key components of life.

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[806] Cf §15.3.

[807] Excerpt from Margulis (1999): ‘If we define life as a reproducing system capable of natural selection, then Gaia is living. The easiest way to see this is through a simple thought experiment. Imagine that a spacecraft carrying microbes, fungi, animals and plants is sent to Mars. Let it produce its own food and cycle its waste, and let it persist for two hundred years. Gaia is the recycling system of life as a whole. A budding off of one Gaia to produce two would have occurred. The construction of such a miniature Gaia would represent de facto reproduction.’

[808] Cf §2.1.

[809] Cf §13.4.

As a conclusion for Part III, Figure 53 contextualises the scope of research question 3 (RQ3) ‘What are the contributions of ACE development to the operationalisation of IE?’ along the research axes of IE and LSS.

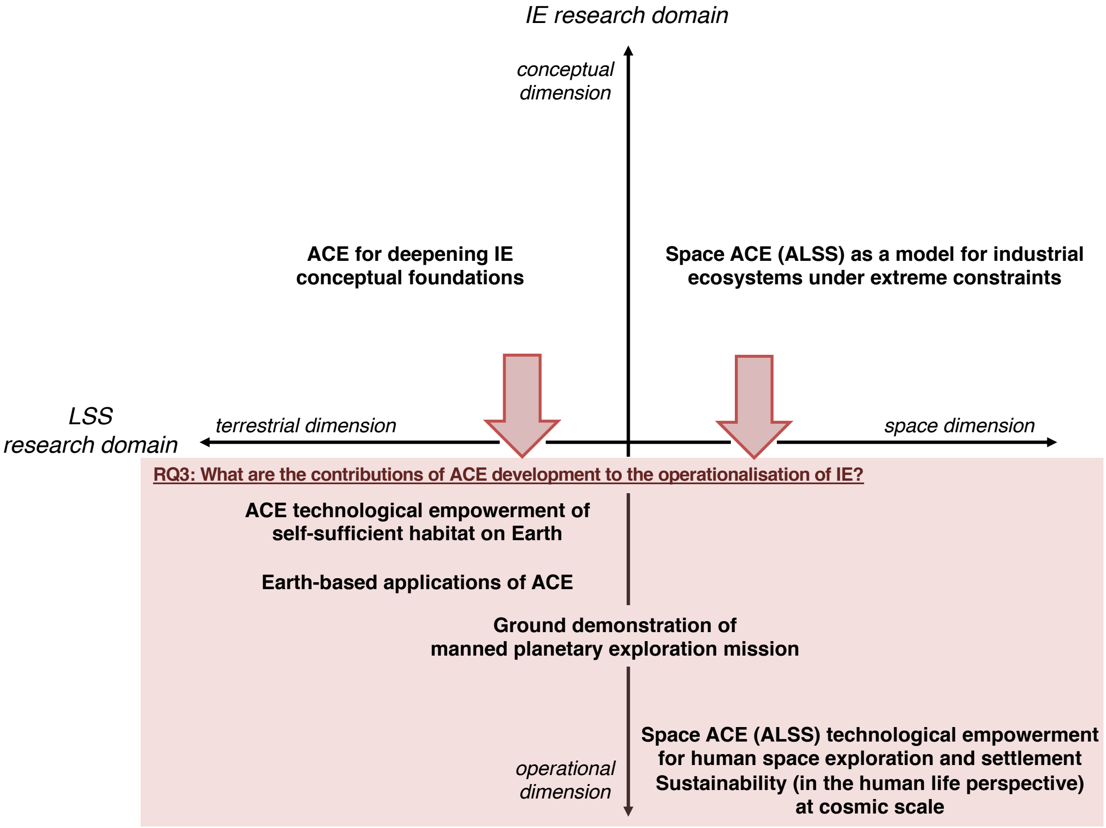


Figure 53: Scope of the research question RQ3 along the research axes of IE and LSS.
The third part of this PhD work tackled the contributions of ACE development to the operationalisation of IE. It analysed the potential of ACE development for the technological empowerment of self-sufficient habitat on Earth. It compiled the contributions of ACE development to terrestrial sustainability. With the benefit of hindsight from the overall outcome of this research, it considered the possible ways to envisage sustainability (in the human life perspective) at cosmic scale.

GENERAL CONCLUSIONS

As general conclusions, this section first discusses the convergence of the research domains of IE and LSS, provides a timeline and mapping of research outputs and ACE-related activities. Then, it provides reflections on the Oïkosmos programme, the ACE demonstrator, closed habitats and the ALSS roadmap, before giving final considerations on this research.

Convergence of the research domains of IE and LSS

The present work fitted within the context of the following major trends:

- The development of the field of industrial ecology, in the broader context of research and development in the area of sustainability (including circular economy, cleaner production, sustainable consumption, etc.), which has been analysed in §2.2, §3, §5.3 and §14.1;
- The development of habitats demonstrating high levels of material closure and self-sufficiency (tiny house, off-grid habitat, autarkic habitat, etc.), as well as featuring proper conditions for a healthy habitat (telework; telehealth, especially for elderly people), in particular with the COVID-19 sanitary crisis of 2020-2021 and its wide implications in terms of biosafety, which have been discussed in §5.6 and §13;
- The growing production of organic and locally sourced food with high nutritional value and the advancement of agriculture in confined space (including vertical/urban farming or 3D-agriculture), which has been presented in §5.4;
- The development of eco-innovation (or responsible innovation), including new business models (product service systems, mHealth, etc.), which has been mentioned in §9 and §14.4;
- The advancement of life support systems for space purposes, and their associated Earth-based applications, in the context of the emergence of New Space, which have been detailed in §4.2, §14.2, 14.4, §15.1, §15.5 and §15.6;
- The recent and spectacular development of the disciplinary fields of systems biology and 'omics' sciences (including metabolomics, microbiomics and nutrigenomics), which have been examined in §5.4;
- The ubiquitous trend of digitalisation, in particular in relation to the fields of information and communication technologies (but also Industry 4.0, smart cities, etc.), artificial intelligence, (Big) Data management and e-Health, which has been approached in §5.5, §9 and §15.6.

Until recently, these trends and themes were characterised by their different origins, distinct evolutions and own development trajectories. One of the objectives of this thesis has been to show how they built on increasing convergences.

Among such a wealth of topics, this work focused more specifically on the convergence of two main research domains – industrial ecology (IE) and life support systems (LSS) –, a convergence that has been further examined in the context of development of closed systems, namely 'artificial closed ecosystems' (ACEs). The choice of studying ACE along the axes of IE and LSS research domains was based on the strong convergence of their development trajectories since the late 1990s/early 2000s. On one hand, this work analysed ACE in the perspective of the domain of IE, and, on the other hand, in the perspective of the experimental framework of LSS, which constituted the two main axes of this research. Both axes of research have been selected because of the complementarity of the dimensions of their research domains, that could position the research on ACE both at theoretical and practical levels.

The first part of this PhD thesis studies the relevance of ACE research to the conceptual foundations of IE. The second part of this work focuses on the possible ways to cross-fertilise the terrestrial and space dimensions of LSS development. The third part of this PhD work tackles the contributions of ACE development to the operationalisation of IE. Figure 54 positions the research objectives along the research axes of IE and LSS.

For the research domain ‘industrial ecology’, a first dimension concentrated on the theoretical aspects of IE and explored how the analysis of ACE can foster and consolidate the conceptual foundations of the field of IE. Through the conceptual background of IE, this thesis addressed both industrial and scientific ecology and particularly aimed at deepening industrial and natural ecosystems analogies in the context of ACE analysis. A second research dimension emphasised on the operationalisation and implementation processes of ACE in the perspective of IE, with various associated case studies as research outputs and spin-off projects.

For the research domain ‘life support system’, a first dimension focused on the use of LSS for space exploration purposes – namely Advanced LSS or ALSS – and more particularly on how to simplify and miniaturise ACE in order to envision long-duration missions for possible human settlements in the Solar System, and possibly beyond, thus radically expanding the notion of sustainability (in the human life perspective) at cosmic scale. The second research dimension was connected to the exploitation of circular systems for terrestrial purposes, either as a whole in a self-sufficient habitat or through the possible uses of the components and technological solutions of ACE for various kinds of Earth-based applications.

Combining the conceptual and terrestrial dimensions underscored the role of ACE for deepening IE conceptual foundations, whereas the confluence of conceptual and space dimensions highlighted how space ACE or ALSS could be considered as a model for industrial ecosystems under extreme constraints. Then, the intersection of operational and terrestrial dimensions showcased the interest, on the one side, of Earth-based applications of ACE and, on the other side, of the technological empowerment by ACE for developing self-sufficient habitat. Next, the coupling of operational and space dimensions displayed the potential of space ACE (ALSS) technological empowerment for human space exploration and settlement and the notion of sustainability (in the human life perspective) at cosmic scale. Finally, ground demonstration of manned planetary exploration mission stood at the interface of terrestrial and space LSS dimensions together with the operational one of IE.

An original facet of this work came from the hybridisation, on the one hand, from the conceptual and operational dimensions of the IE domain and, on the other hand, from the integration of the theoretical and experimental aspects of ACE research. In particular, it was highlighted how the approach for apprehending ACE reflects the dual dimension of the field of study and action of IE for the analysis and the transformation of the industrial system. Another specificity of this thesis was illustrated by its synergistic approach for the study of terrestrial and space orientations of ACE along the LSS axis.

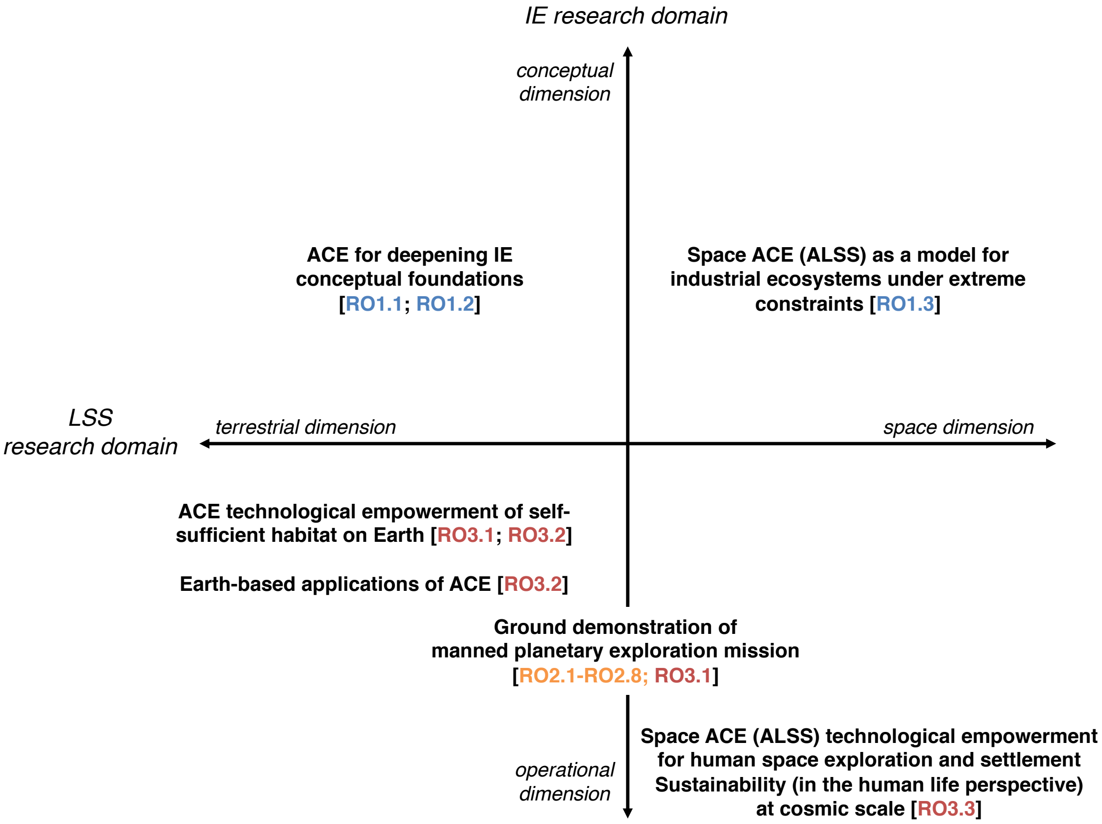


Figure 54: Positioning of research objectives along the research axes of IE and LSS.

What is the relevance of ACE research to the conceptual foundations of IE? (RQ1):

- *to review the analogy between the natural and industrial ecosystems (RO1.1);*
- *to propose key concepts for ACE analysis in the perspective of IE and investigate their relevance for consolidating the conceptual foundations of IE (RO1.2);*
- *to examine space ACE (ALSS) as a model for industrial ecosystems under extreme constraints (RO1.3).*

How to cross-fertilise the terrestrial and space dimensions of LSS development? (RQ2):

- *to formulate a research agenda for the Oïkosmos science and technology programme dedicated to the establishment of space and terrestrial research synergies on ACE (RO2.1);*
- *to assess how to develop and exploit a ground demonstrator of ACE as a leading technological platform for the study of circular systems (RO2.2);*
- *to explore, map and assess Swiss activities, interests and strengths in LSS (RO2.3);*
- *to demonstrate the terrestrial and space research synergy potential through the elaboration and consecutive implementation of a concrete R&D project (spin-in or spin-out) (RO2.4);*
- *to illustrate a possible co-development technology roadmap for LSS development with an exemplifying prototyping project (spin-in or spin-out) (RO2.5);*
- *to elaborate a stakeholder engagement strategy for consolidating the current Swiss activities and rationale for LSS and MELiSSA development into an active and productive cluster (RO2.6);*
- *to expose the opportunities offered by the hosting an ACE demonstrator in Western Switzerland for its innovation ecosystem and for the Swiss space sector (RO2.7);*
- *to foster the institutional dynamics for ACE and LSS development in Switzerland and promote related education and communication activities (RO2.8).*

What are the contributions of ACE development to the operationalisation of IE? (RQ3):

- *to analyse the potential of ACE development for the technological empowerment of self-sufficient habitat on Earth (RO3.1);*
- *to determine the contributions of ACE development to terrestrial sustainability (RO3.2);*
- *to investigate the possible ways to envisage sustainability (in the human life perspective) at the cosmic scale (RO3.3).*

Timeline and mapping of research outputs and ACE-related activities

This PhD thesis manuscript gathers together diverse research outputs related to the research activities as a PhD candidate, assistant, and research fellow at the University of Lausanne since 2008, as well as co-founder and managing director of Earth Space Technical Ecosystem Enterprises SA (ESTEE) since 2013. Figure 55 gives the chronology of research outputs and of ACE-related institutional, educational and communication activities implemented during the elaboration of this PhD work.

These research outputs have been developed through a back-and-forth process, with initially a more space-oriented centre of attention on the research agenda preparation of human space exploration in ground simulators (Oïkosmos Report), followed by the deployment of prototyping activities of such simulator as well as the development of Earth-based applications of ACE through the activities of ESTEE, which aims to develop an ACE demonstrator, namely the Scorpius Prototype 1, as well as with joint projects such as ESA's BELiSSIMA and Assessment of financial business potential of ALSS. In parallel, other projects with both space and terrestrial focal points have been pursued like Swiss Position Paper and SUMIT projects.

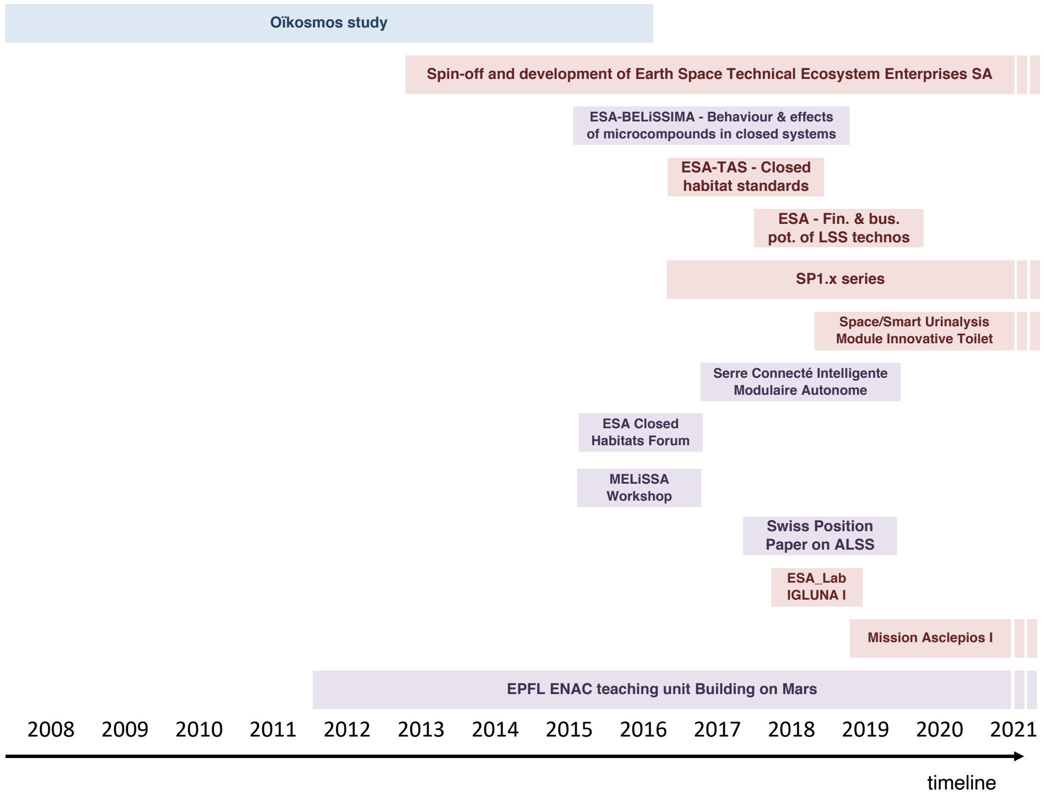


Figure 55: Chronology of research outputs and ACE-related institutional, educational and communication activities. Activities generated within the implementation of the PhD thesis are coloured depending on the organisation leading the project: Activities led by UNIL in blue, led by ESTEE and based on the activities from Oïkosmos Report in red, joint contribution of both UNIL and ESTEE is highlighted in purple.

As illustrated in Figure 56, the research outputs can be considered either on the conceptual or on the operational dimension of the IE axis. Figure 57 described the relation of the research of outputs along the fields of research of the Oïkosmos programme.

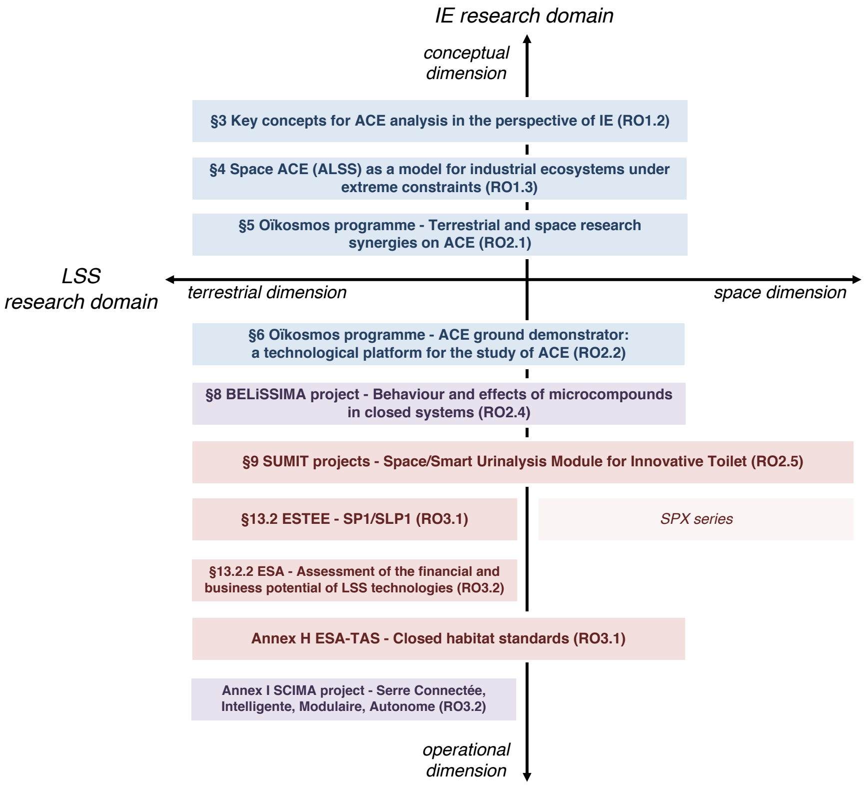
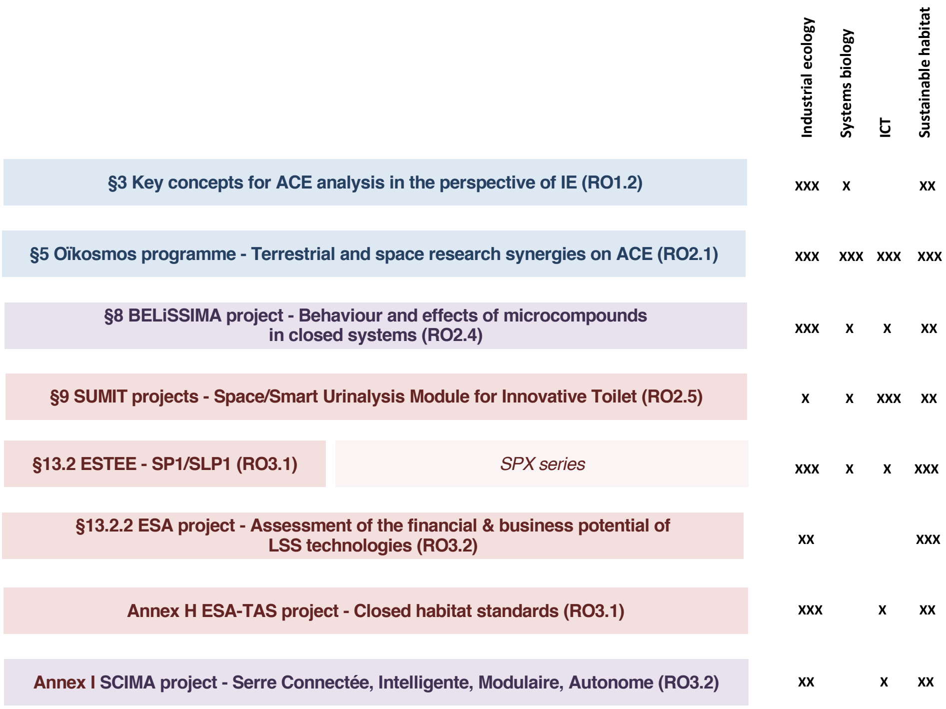


Figure 56: Positioning of ACE-based projects as research outputs along the LSS research axis. Activities generated within the framework of the PhD thesis are coloured depending on the organisation leading the project: Activities led by UNIL in blue, led by ESTEE and based by the spin-off activities from Oïkosmos Report in red, joint contribution of both UNIL and ESTEE is highlighted in purple.



	Industrial ecology	Systems biology	ICT	Sustainable habitat
§3 Key concepts for ACE analysis in the perspective of IE (RO1.2)	xxx	x		xx
§5 Oïkosmos programme - Terrestrial and space research synergies on ACE (RO2.1)	xxx	xxx	xxx	xxx
§8 BELiSSIMA project - Behaviour and effects of microcompounds in closed systems (RO2.4)	xxx	x	x	xx
§9 SUMIT projects - Space/Smart Urinalysis Module for Innovative Toilet (RO2.5)	x	x	xxx	xx
§13.2 ESTEE - SP1/SLP1 (RO3.1) SPX series	xxx	x	x	xxx
§13.2.2 ESA project - Assessment of the financial & business potential of LSS technologies (RO3.2)	xx			xxx
Annex H ESA-TAS project - Closed habitat standards (RO3.1)	xxx		x	xx
Annex I SCIMA project - Serre Connectée, Intelligente, Modulaire, Autonome (RO3.2)	xx		x	xx

Figure 57: Research outputs along the Oïkosmos research fields of IE, systems biology, ICT and sustainable habitat.

In order to provide a high-level overview, the ACE and LSS activities elaborated in the framework of this thesis work can be mapped as follows, based on the MELiSSA-related themes:

- Basic research and development:
    - Key elements from the concept of industrial ecology (§2);
    - Key concepts for artificial closed ecosystems analysis (ACE) in the perspective of scientific and industrial ecology (§3);
    - Space ACE as a model for industrial ecosystems under extreme constraints (§4);
    - Oïkosmos Report (§5);
    - BELISSIMA phase A (§8);
    - Closed habitat (CH) as minimal habitat for self-sufficiency in the perspective of IE (§13.4);
    - Extending space sustainability to cosmic scale (§15.5);
    - Contributions of ACE development to space sustainability (§15.6).
- Ground demonstration:
    - Oïkosmos Report (§5);
    - Modalities of uses of an ACE demonstrator as a technological platform (§6.2);
    - Towards an ACE ground demonstrator in Western Switzerland (§11);
    - Scorpius Prototype (SP1) and Scorpius Laboratory Prototype (SLP1)(§13.2);
    - ESA TAS – Towards the establishment of a standard on CH specifications (Annex H).
- Terrestrial applications:
    - SUMIT project - Smart Urinalysis Module for Innovative Toilet and Space Urinalysis Module for Innovative Toilet (§9);
    - Mapping of Earth-based applications of ACE (§14.2);
    - ESA Study for the assessment of the financial and business potentials of LSS technologies (§14.2.2);
    - Contributions of ACE development to circular economy (§14.4);
    - SCIMA project - Serre Connectée, Intelligente, Modulaire, Autonome (Annex I).
- Education and communication:
    - Position Paper on Advanced LSS (§7).
    - Stakeholder engagement strategies (§10);
    - ESA Closed habitat Forum (§10.1);
    - MELiSSA scientific workshop (12.2);
    - EPFL ENAC teaching unit Building on Mars (§12.3);
    - ESA_Lab IGLUNA Project (Annex F3) and Mission Asclepios (Annex F4).

Oïkosmos programme

Oïkosmos does not pretend to solve everything that concerns ecology. It is primarily a closed-system ecology project in which recycling is exacerbated by the narrowness of the site. But if one aspires that the study of such very significantly reduced model can truly offer advice for solving larger issues – i.e. on the scale of the whole planet – inextricably linked to terrestrial sustainability, it seems necessary to extract some of their functions in order to size them on a larger scale (case of decentralised recycling of wastewater), or to include an additional external supply (case of the contribution of CO_2 allowing to largely extend the quantity of organic molecules circulating in the system).

Oïkosmos is an audacious project that seems to be able to create a decisive momentum for the development of research on closed systems. A key challenge is to go beyond the standard vision of a specific development on space, separated from the terrestrial one, or at least implement sequentially, and to envision it rather a synergistic way, within a co-development process. Therefore, the *raison d'être* of Oïkosmos is about the fact that synergies of R&D between manned space missions and terrestrial issues can benefit both.

Furthermore, the ACE research agenda allows questions to be formulated under extreme conditions. It is therefore conceivable that the answers found could enable the development of applications that would not have been identified under normal conditions.

One of the purposes of Oïkosmos is to accelerate ACE development. Of course, the realisation of such an ambitious research programme will still require many scientific and technological advances. In the meantime, Oïkosmos could serve as a springboard for the technological development of innovative and exemplary solutions, with promising terrestrial ACE applications based on the use of a module or technology, or a combination of them. The positive spillovers of the dissemination of these new or emerging technologies from the Oïkosmos programme should contribute, at their own scale, to the resolution of pressing issues and challenges facing European society, both in terms of environmental and human health management.

ACE demonstrator

In such context, a complete European ACE demonstrator would become a place for implementing integrative science and technology developments and blurring the boundaries between space and terrestrial experimental R&D research. It would play more than ever a key role in cross-fertilising this dual scientific and technological LSS roadmaps.

With its strong connections to both space and terrestrial sustainability, it appears that ACE development should keep a down-to-Earth mindset focused on scientific exploration and Earth-based applications, to engage and federate a maximum of stakeholders and reach the widest possible audience.

Therefore, a thoughtful and balanced mix of researchers, specialists and experts collaborating at all levels of the 'Research-Innovation-Market' value chain would thus position the ACE demonstrator both as a driver of eco-innovation and as an amplifier of interactions and partnerships. In addition, it would represent a new kind of testbed and a formidable instrument for promoting the development of innovative applications and solutions. In the long term, it should become a technological showcase for 'made in Europe' applications at the convergence of space and terrestrial sectors, which would enhance credibility and shape a global and constructive opinion around ACE development.

In conclusion, an ACE demonstrator is essential to implement the space and terrestrial R&D agenda on LSS. Furthermore, such Earth-based experimental closed facility would be instrumental for further improving and developing LSS technologies as well as new methods and thinking, and particularly for engaging new stakeholders from space and terrestrial organisations, and integrating the latest technological progress made in other R&D fields.

Closed habitats

Space exploration allows us to better understand life in confinement. With its sudden imposed restricted living conditions since early 2020, the COVID-19 pandemics indirectly illustrated the immense challenge of confinement in space vehicles and the relevance of ACE subsystems wide diffusion for the benefit of citizens. More concretely, the ongoing sanitary crisis created a new stay-at-home economy for shopping, working, learning, cooking, health and entertainment. Its impacts showed the importance of LSS technologies (e.g. remote health monitoring, microbial safety, air quality management, etc.) for proactive and reactive health management (habitat environment monitoring, point-of-care diagnostic, household and personal cleaning with antiseptic liquid and sanitisers) or on-site pantry preparation in self-sufficient habitat.

Beside its strong technical and scientific requirements, an ACE demonstrator consists above all of an LSS for humans. More than a technological dependence, it provides to human a vital connection, a bubble sustaining life. Nonetheless, the final vision of a CH is not just ensuring the survival at the individual level. Rather, it aspires to link a technical approach to human, social and environmental concerns. In return, it makes it possible to revisit what is living and what is a ‘home’ at the level of a minimal habitat, crucial for dealing both with space and terrestrial sustainability issues.

By reconditioning to human purpose a limited set of simplified ecosystems processes and services within a liveable habitat, CH have the capacity to ensure self-sufficiency for one or a few occupants. A CH can be considered as a minimal habitat, a living unit for long-duration dwelling within a sustainable habitat, a man-made closed ecosystem for humans.

ALSS roadmap

The completed crewed closed experiments of ALSS so far are all Earth-based experiments, which differ deeply with extraterrestrial environment in terms of gravity, magnetic fields or radiations. Consequently, long-term operations of ACE must be carried out in a space context such as in a space station, on the Moon or on Mars to ensure their proper calibration and progressively established a safe crewed space ACE.

The high quality of the European scientific and engineering approach can continue to benefit from this common, multilateral, and multidisciplinary effort in leveraging further human space exploration together with the development of thriving spin-out applications, an epic journey full of businesses. In the coming decade, such continuation nonetheless implies to consolidate a clear, harmonised and robust strategy at European level (Lasseur 2020).

Even if at the moment, and possibly still for a while, standard physico-chemical LSS are the norm for space exploration with increased levels of loop closure and higher reliability, we will eventually rely on synthetic, engineered and highly controlled biospheres to provide a tasty diet based on the transformation of waste into edible food. Advanced, microbiology-based LSS will be progressively phased in, as their maturity progresses, and as they present many benefits to the crew. The purpose of this work was to highlight those advantages, that go much beyond the crew, with the terrestrial spin-off solutions of which would benefit for the citizens.

For the first time in 30 years, regenerative life support is part of ESA exploration roadmap through the Terrae Novae programme (ESA Industrial Policy Committee 2021), which is ESA’s European Exploration Envelope Programme (E3P) bringing together all ESA exploration activities and missions into a single programme. ESA is not positioning itself only as a transporter but now, as well as a habitat designer and developer. This could start with the full development of a habitation module, potentially connected to ISS or CIS Lunar orbiter to demonstrate and validate the necessary LSS and health technologies for the Mars transit phase. A preliminary study is supposed to be concluded for ESA ministerial council of November 2022.

Final considerations

Humans act as a catalyst of evolution and are now transforming their surrounding environment at all scales, as strikingly illustrated by what seems to be the unstoppable development of New Space. ACE development must embrace this technological progress and make the best out of the ongoing space industrialisation. New Space should clearly become a key driver for the next decades manned planetary exploration, and its potential to indirectly enhance space ACE development is real. In particular, with the current booming of commercial space-based start-ups and space-driven private ventures, space ALSS should gain more visibility and accelerate its development.

Nonetheless, in the light of the expansion of New Space, a distinction should especially be made between space tourism, exploitation, exploration and settlement. Even if a permanent settlement on another planet, on the Moon or in a space station requires the use of ACE, one should avoid confusing the issues of long-term space exploration missions with space industrialisation at the Solar System scale.

The next frontier for sustainability is space. Such extension of sustainability scope involves the integration of the terrestrial scale with the scale of Solar System, and even beyond. ACE encode narratives on the way space sustainability can take place and are of major importance for overcoming the pitfalls of space sustainability. By disseminating and applying the lessons learnt in closed systems, ACE promoters – such as MELiSSA partners and ESTEE – are operationalising the principles of IE, and thus enabling the effective implementation of the megatrend of sustainability at practical levels for positive societal returns.

ACE and LSS are eye-openers to the benefits of bioinspiration. They open up new avenues for the control and regulation of ecosystems leading to new facets of interpreting nature and the improvement of health in general within a CH. It can be deduced from this work that the realisation of the promises of ACE development will depend on an open and constructive dialogue between medicine, biology, humanities and environmental sciences, enabled by engineering and digitalisation capacities.

All in all, space exploration is about preparing the future, in a sense that it should benefit the Earth right now, and be instrumental for the betterment of society. Therefore, human space exploration could be considered as a topic of the upmost importance simply because of the value of the Earth-based applications of space ACE technologies.

Even if manned long-duration and remote space missions would not be carried out, research for hyper-efficient space ACE is worth doing anyway not only due to the growing constraints on Earth, but to their potential for the sustainable resource management on Earth. Therefore, this research anticipates that ACE components will be developed in any case for their relevance for terrestrial sustainability, and their market applicability into everyday life.

Because of its orientation towards circularity, its eco-innovative nature, together with its broad field of application, the research on ACE and LSS has the potential to occupy a central position in the development of IE.

As evidenced by this thesis, research on ACE and LSS is an excellent instrument to forge a sustainable future, by elaborating more closed industrial ecosystems, more sustainable in the face of decreasing supplies of raw materials and increasing problems of waste and pollution. Therefore, synergies of terrestrial and space R&D on ACE and LSS can act as drivers for implementing sustainability, in the perspective of IE.

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ANNEXES

The following annexes are provided in separated files:

- ANNEX A - Oïkosmos Report - Le programme 'Oïkosmos': Synergies de recherches terrestre et spatiale sur les écosystèmes clos artificiels :
    - Annex A1 - Oïkosmos Report - Full report (520 pages);
    - Annex A2 - Stakeholders of Oïkosmos Report.
- ANNEX B - Position Paper - Consolidating the Swiss activities and rationale for ALSS and MELiSSA development:
    - Annex B1 - Position Paper - Full report (95 pages);
    - Annex B2a - Position Paper - MELiSSA conference 2020 – Abstract (1 page);
    - Annex B2b - Position Paper - MELiSSA conference 2020 – Presentation (17 slides).
- ANNEX C - BELISSIMA Phase A (confidential documents):
    - Annex C1 - BELiSSIMA Phase A - Detailed proposal AO/1-8342/15/NL/AT (132 pages);
    - Annex C2a - MELiSSA TN 118.1.4 - Review of terrestrial closed ecosystems studies (99 pages);
    - Annex C2b - MELiSSA TN 118.1.6 - Development of a stakeholder engagement strategy (27 pages + annexes);
    - Annex C2c - MELiSSA TN 118.2 - The future of BELISSIMA: roadmap and recommended Frame of Work (64 pages).
- ANNEX D - SUMIT proposals (confidential documents):
    - Annex D1 - Mesures de Positionnement (MdP) - Call for Proposals 2020: Development of SUMIT (Space Urinalysis Module for Innovative Toilet): Crew health monitoring and support of ALSS functionnality (51 pages);
    - Annex D2 - Innocheque technical report - Health Monitoring Toilet (703-CT.2035, Innosuisse Voucher 49466.1 INNO-ENG) (28 pages);
    - Annex D3 - Innosuisse application - Impulse Programme innoCH: SUMIT - Smart Urinalysis Module for an Innovative Toilet (55059.1 IP-ENG):
        - Annex D3a - Online application (60 pages);
        - Annex D3b - Business plan for the SUMIT project (32 pages).
- ANNEX E - ESA Closed Habitats Forum:
    - Annex E1 - ESA Closed Habitats Forum online programme (11 pages);
    - Annex E2a - Forum methodology guidelines (7 pages);
    - Annex E2b - Forum recommendation canvas (1 page) ;
    - Annex E3 - ESA Closed Habitats Forum - Main conclusions and recommendations (16 pages).
- ANNEX F - Education and communication activities:
    - Annex F1a - MELiSSA scientific workshop book of abstracts (93 pages);
    - Annex F1b - Abstract and slides of Oïkosmos presentation (6 pages);
    - Annex F2a - EPFL ENAC teaching unit Building on Mars - PENS-304 – Organisation (9 pages);
    - Annex F2b - EPFL ENAC teaching unit Building on Mars - PENS-304 - Examples of student deliverables on LSS (125 pages);
    - Annex F2c - EPFL ENAC teaching unit Building on Mars - PENS-304 - Article published in Proceedings of the International Conference Structures and Architecture 2013 (8 pages);
    - Annex F3 - ESA_Lab Demonstrator Project: IGLUNA – 'A habitat in ice' – Brochure and modules list (40 pages);
    - Annex F4 - Mission Asclepios I – Mission report (113 pages).

- ANNEX G - ESTEE Scorpius Prototype 1:
    - Annex G1 - ESTEE Scorpius Prototype 1 presentation, EMC18, La Chaux-de-Fonds, 26.10.2018 (44 pages).
- ANNEX H - ESA-TAS Towards the Establishment of a Standard on Closed Habitat Specifications (confidential documents):
    - Annex H1 - ESA-TAS - Quotation - Reference 1300046707 (5 pages);
    - Annex H2 - ESA-TAS Statement of Work - Reference ESA-TECMMG-SOW-009775 (6 pages);
    - Annex H3 - ESA-TAS ESTEE - Technical Note 1 Final Report (38 pages).
- ANNEX I - SCIMA project - Serre Connectée, Intelligente, Modulaire, Autonome (confidential documents) :
    - Annex I1 - Fiche pré-projet 2014-2020 Programme Interreg V France-Suisse du 04.04.2017 (21 pages);
    - Annex I2 - Convention d’utilisation des aides au titre du Programme Interreg V France-Suisse 2014-2020 du 10.01.2018 (7 pages);
    - Annex I3 - Example of intermediary deliverables: WP B3 - Projet SCIMA : Rapport de définition du système substrat et irrigation (12 pages).
- ANNEX J - ESA study for the assessment of the financial and business potentials of LSS technologies (confidential documents):
    - Annex J1 - ESA AO/1-9556/18/NL/AT - Proposal (50 pages);
    - Annex J2 - ESA AO/1-9556/18/NL/AT - Final deliverable (1 table);
    - Annex J3 - ESA AO/1-9556/18/NL/AT – Interview grid (91 pages).

ANNEX A - Oïkosmos Report - Le programme ‘Oïkosmos’: Synergies de recherches terrestre et spatiale sur les écosystèmes clos artificiels

Figure 58 shows the structuration of the Oïkosmos Report , which consists of five parts (and respective chapters in the report):

- Part I: Introduction, methodology and context of the report (Annex A-§1 to §4);
- Part II: Oïkosmos programme - Terrestrial and space research synergies on ACE (RO2.1; Research output summary in §5; Annex A-§5 to §11);
- Part III: ACE ground demonstrator: a leading technological platform for the study of circular systems (RO2.2; Research output summary in §6; Annex A-§12 to §19);
- Part IV: Towards an ACE ground demonstrator in Western Switzerland? (RO2.7; Research output summary in §11; Annex A-§20 to §22);
- Part V: Accompanying measures, recommendations and conclusions (RO2.8.a; Research output summary in §12.1; Annex A-§23 to §25).

The Oïkosmos Report include:

- a synthesis report in French (in PDF format) of 520 pages based on the document review, telephone interviews and visits conducted (Annex A1);
- a synoptic table (in MS Excel format) summarising all the structures, organisations and stakeholders in Western Switzerland identified (nearly 400 in total) and/or contacted (90 were interviewed) with their main contact details, keyword assignment and reference to the corresponding chapters of this report (Annex A2).

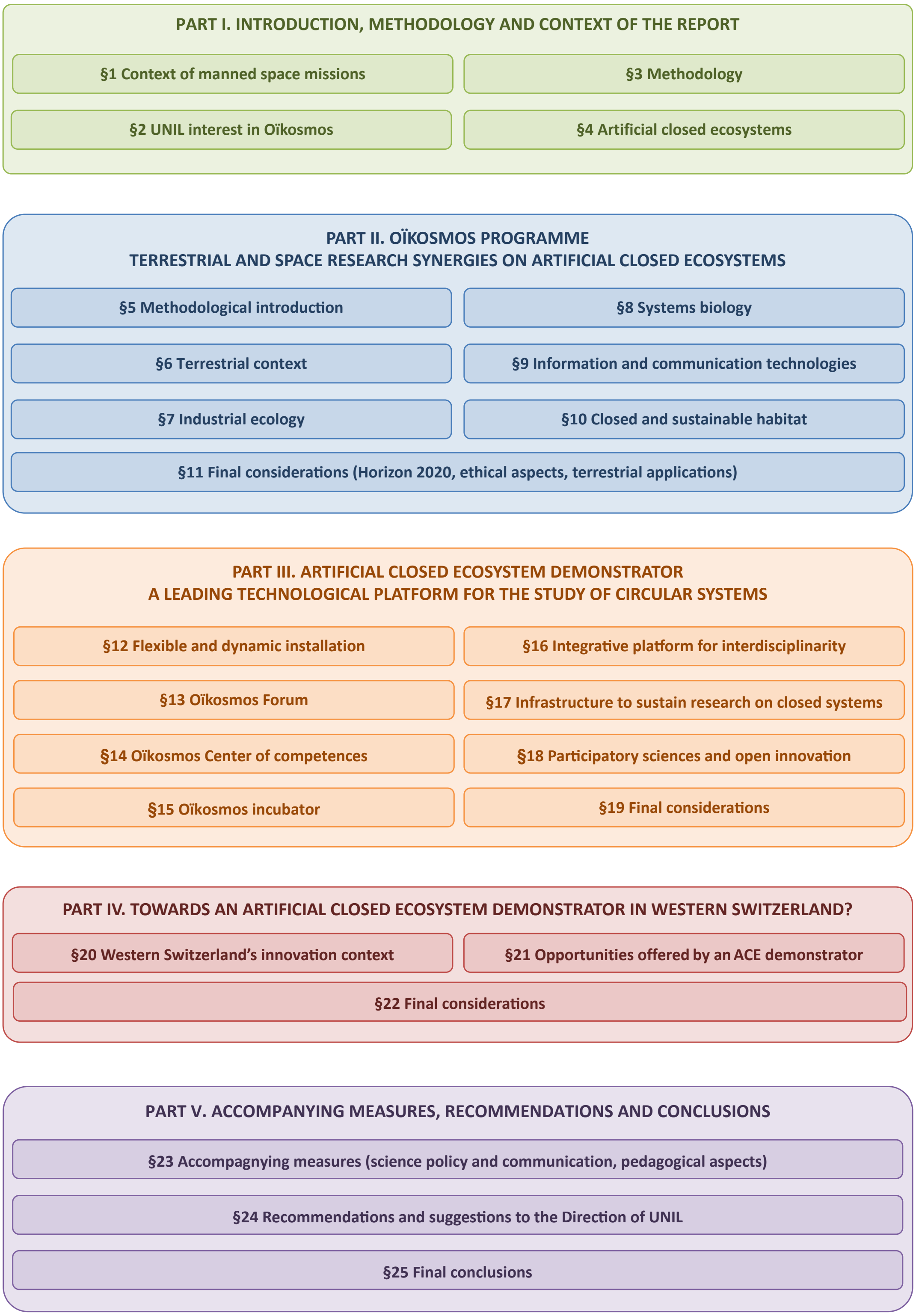

Figure 58: Structuration of Oïkosmos Report.
Part I introduces the context of manned space missions and ACE, as well as the interest of UNIL in Oïkosmos programme and its methodology. In parallel to the formulation of a research agenda for the Oikosmos programme (Part II) and the identification of the opportunities for technology transfer of a ACE demonstrator (Part III), the activities of Part IV consist in establishing a brief overview of the innovation ecosystem in Western Switzerland (§20) and in demonstrating the opportunities offered by hosting an ACE demonstrator in Western Switzerland (§21). On the basis of the activities carried out in Parts I to IV, Part V proposes accompanying measures to promote the Oikosmos programme (§23), and makes recommendations and suggestions to the Direction of UNIL (§24), before concluding the report in §25.

ANNEX B - Position Paper - Consolidating the Swiss activities and rationale for ALSS and MELiSSA development

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ANNEX C - BELISSIMA Phase A (confidential documents)

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ANNEX G - ESTEE Scorpius Prototype 1 presentation

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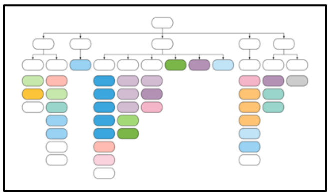
- Annex G - ESTEE Scorpius Prototype 1 presentation, EMC18, La Chaux-de-Fonds, 26.10.2018 (44 pages).

ANNEX H - ESA-TAS Towards the Establishment of a Standard on Closed Habitat Specifications (confidential documents)



Project title: ESA TAS – Towards the establishment of a standard on closed habitat specifications (reference 130046707)

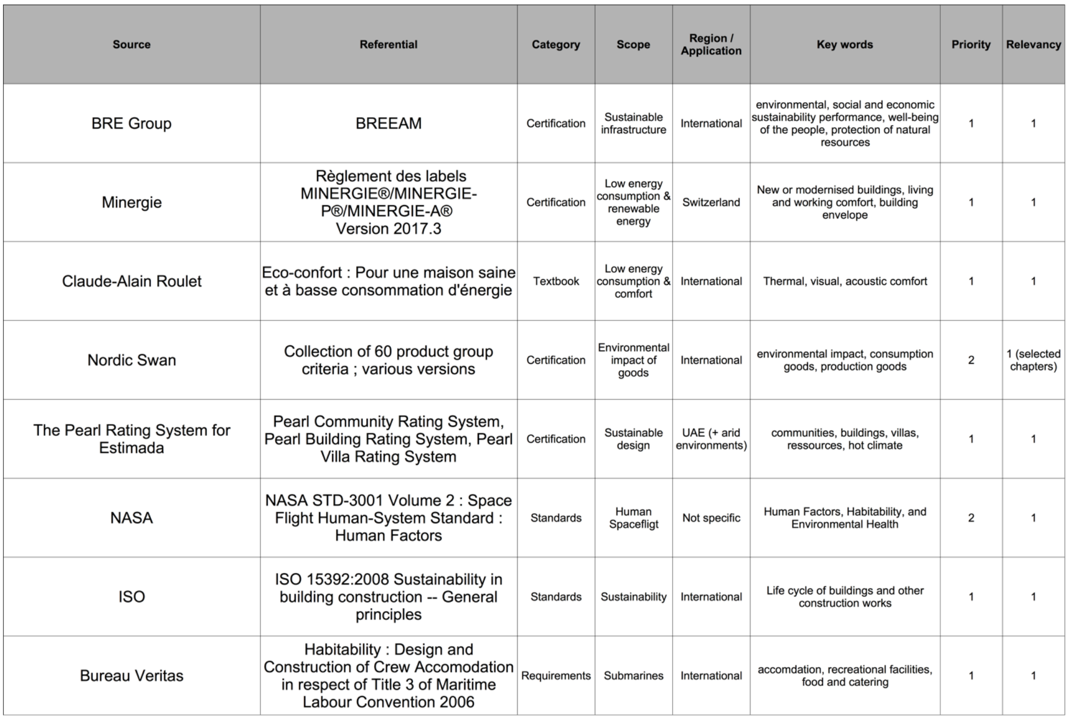
Client: ESA

Contractor: ESTEE

Dates: 2018-2019

The notion of habitat has evolved over time. Further defining standard and norms of CH can contribute to shape the habitat of tomorrow. In this perspective, ESTEE pursued with ESA a TAS (‘technology assessment’) project, which scope was the development of a roadmap establishing standards for CHs, as a follow-up to the conclusions of the ESA Closed Habitats Forum in 2016[810].

With the objective of creating a preliminary reference frame for the development of such standards (Annex H1 and H2), ESTEE searched for referentials applicable to CHs (over 50 reviewed in total, see Figure 59), selected the most relevant ones and compiled there them visually into a final consolidated diagram. To do so, the main topics and subtopics originating from the referentials were identified, arranged by level of application (equipment, habitat and environment) and grouped by topics (air, water, location, etc.) and subtopics (Figure 60). Figure 61 shows the scope (design or technically oriented) and specificity (general or specific) of the selected standards. This information was then used as a structured layout for further developing applicable standards. Such standardisation process would facilitate the technological empowerment of self-sufficient habitat on Earth and the contribution of ACE development to the operationalisation of IE.



Source	Referential	Category	Scope	Region / Application	Key words	Priority	Relevancy
BRE Group	BREEAM	Certification	Sustainable infrastructure	International	environmental, social and economic sustainability performance, well-being of the people, protection of natural resources	1	1
Minergie	Règlement des labels MINERGIE®/MINERGIE-P®/MINERGIE-A® Version 2017.3	Certification	Low energy consumption & renewable energy	Switzerland	New or modernised buildings, living and working comfort, building envelope	1	1
Claude-Alain Roulet	Eco-confort : Pour une maison saine et à basse consommation d'énergie	Textbook	Low energy consumption & comfort	International	Thermal, visual, acoustic comfort	1	1
Nordic Swan	Collection of 60 product group criteria ; various versions	Certification	Environmental impact of goods	International	environmental impact, consumption goods, production goods	2	1 (selected chapters)
The Pearl Rating System for Estimada	Pearl Community Rating System, Pearl Building Rating System, Pearl Villa Rating System	Certification	Sustainable design	UAE (+ arid environments)	communities, buildings, villas, ressources, hot climate	1	1
NASA	NASA STD-3001 Volume 2 : Space Flight Human-System Standard : Human Factors	Standards	Human Spacefligt	Not specific	Human Factors, Habitability, and Environmental Health	2	1
ISO	ISO 15392:2008 Sustainability in building construction -- General principles	Standards	Sustainability	International	Life cycle of buildings and other construction works	1	1
Bureau Veritas	Habitability : Design and Construction of Crew Accomodation in respect of Title 3 of Maritime Labour Convention 2006	Requirements	Submarines	International	accomdation, recreational facilities, food and catering	1	1

Figure 59: Examples of CH-related standards[811] and referentials reviewed in ESA TAS project.

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[810] Cf §10.1.

[811] Full list (50+ standards) in Annex H3.

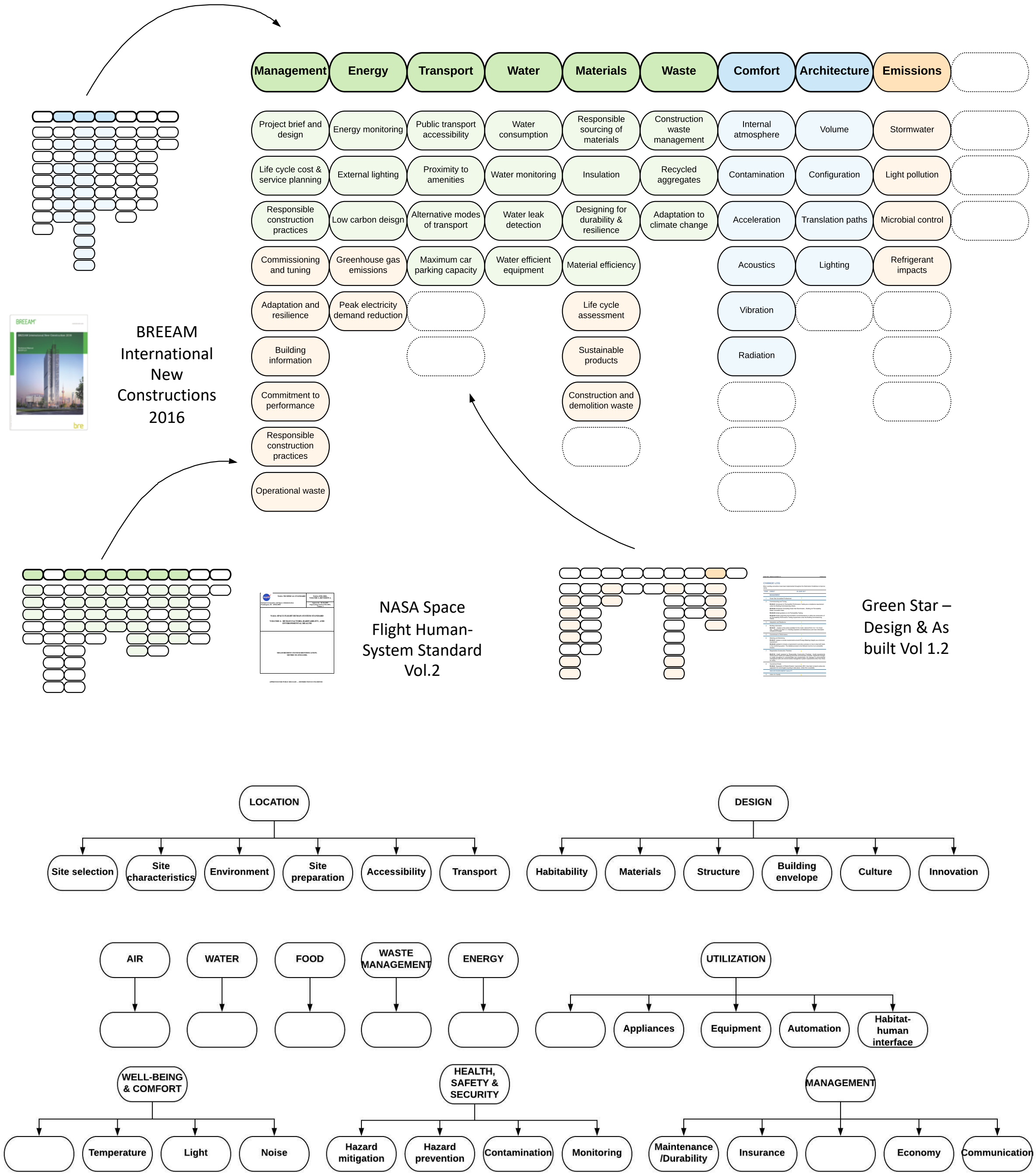

Figure 60: Data consolidation for establishing a preliminary standard on CHs in ESA TAS project. Reviewed standards' CH-related sections/contents were arranged by level of application and grouped by topic (e.g. location, design, air, water, etc.) and subtopics (e.g. for location: site selection, site characteristics, environment, site preparation, accessibility, transport) and then compiled in a visual mapping[812].

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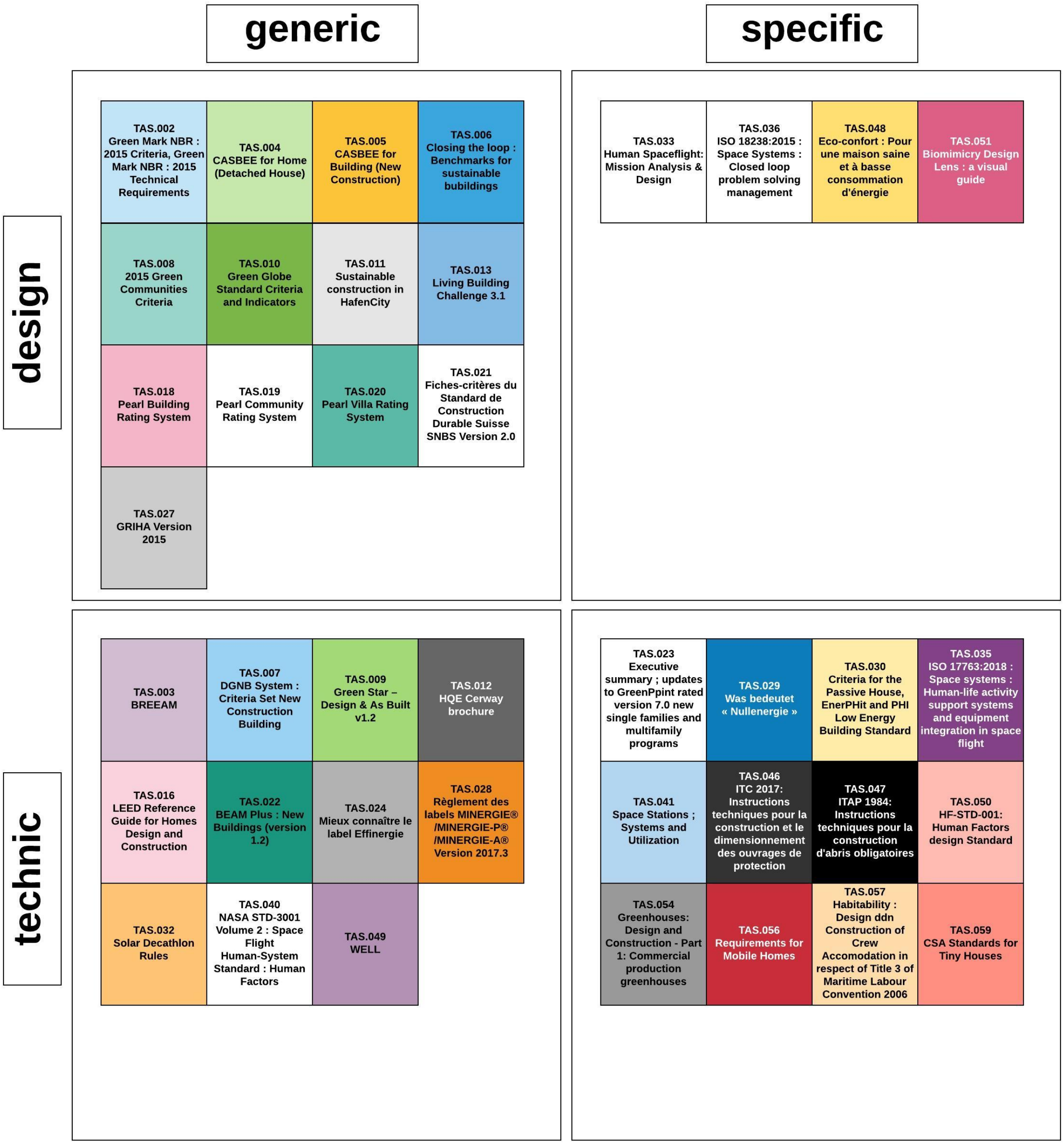
[812] All visual mapping available in Annex H3.



generic

specific

design

technic

design – generic

- TAS.002 Green Mark NBR : 2015 Criteria, Green Mark NBR : 2015 Technical Requirements
- TAS.004 CASBEE for Home (Detached House)
- TAS.005 CASBEE for Building (New Construction)
- TAS.006 Closing the loop : Benchmarks for sustainable bubildings
- TAS.008 2015 Green Communities Criteria
- TAS.010 Green Globe Standard Criteria and Indicators
- TAS.011 Sustainable construction in HafenCity
- TAS.013 Living Building Challenge 3.1
- TAS.018 Pearl Building Rating System
- TAS.019 Pearl Community Rating System
- TAS.020 Pearl Villa Rating System
- TAS.021 Fiches-critères du Standard de Construction Durable Suisse SNBS Version 2.0
- TAS.027 GRIHA Version 2015

design – specific

- TAS.033 Human Spaceflight: Mission Analysis & Design
- TAS.036 ISO 18238:2015 : Space Systems : Closed loop problem solving management
- TAS.048 Eco-confort : Pour une maison saine et à basse consommation d'énergie
- TAS.051 Biomimicry Design Lens : a visual guide

technic – generic

- TAS.003 BREEAM
- TAS.007 DGNB System : Criteria Set New Construction Building
- TAS.009 Green Star – Design & As Built v1.2
- TAS.012 HQE Cerway brochure
- TAS.016 LEED Reference Guide for Homes Design and Construction
- TAS.022 BEAM Plus : New Buildings (version 1.2)
- TAS.024 Mieux connaître le label Effinergie
- TAS.028 Règlement des labels MINERGIE® /MINERGIE-P® /MINERGIE-A® Version 2017.3
- TAS.032 Solar Decathlon Rules
- TAS.040 NASA STD-3001 Volume 2 : Space Flight Human-System Standard : Human Factors
- TAS.049 WELL

technic – specific

- TAS.023 Executive summary ; updates to GreenPpint rated version 7.0 new single families and multifamily programs
- TAS.029 Was bedeutet « Nullenergie »
- TAS.030 Criteria for the Passive House, EnerPHit and PHI Low Energy Building Standard
- TAS.035 ISO 17763:2018 : Space systems : Human-life activity support systems and equipment integration in space flight
- TAS.041 Space Stations ; Systems and Utilization
- TAS.046 ITC 2017: Instructions techniques pour la construction et le dimensionnement des ouvrages de protection
- TAS.047 ITAP 1984: Instructions techniques pour la construction d'abris obligatoires
- TAS.050 HF-STD-001: Human Factors design Standard
- TAS.054 Greenhouses: Design and Construction - Part 1: Commercial production greenhouses
- TAS.056 Requirements for Mobile Homes
- TAS.057 Habitability : Design ddn Construction of Crew Accomodation in respect of Title 3 of Maritime Labour Convention 2006
- TAS.059 CSA Standards for Tiny Houses

Figure 61: Scope (design or technically oriented) and specificity (general or specific) of the selected standards.

Annex H is composed of the following confidential documents which are provided in separated files:

- Annex H1 - ESA-TAS - Quotation - Reference 1300046707 (5 pages);
- Annex H2 - ESA-TAS Statement of Work - Reference ESA-TECMMG-SOW-009775 (6 pages);
- Annex H3 - ESA-TAS ESTEE - Technical Note 1 Final Report (38 pages).

ANNEX I - SCIMA project (confidential documents)

Framework: Programme Interreg V France-Suisse

Collaborators: ESTEE, UNIL, Grangeneuve, Groupe Brunet, USMB

Date: 2017-2019

In 2017, ESTEE was awarded for the implementation of an INTERREG project, with the participation of UNIL and the agricultural institute of Grangeneuve for developing a smart connected, modular and autonomous greenhouse, through the SCIMA project (Serre Connectée, Intelligente, Modulaire, Autonome), and thus connecting wastewater recycling with fresh food production in a decentralised way on a small scale. The system was aimed to increase the biocapacity of constraining environments in terms of resources generation (fresh food) and absorption of what comes from consumption (waste valorisation, while limiting the environmental footprint as much as possible. The initial targeted areas application were urban or mountainous (typical of the cross-border INTERREG region). Initially funded with a budget of CHF 928’000.-, the project had unfortunately to be stopped after mid-project completion, due to the withdrawal of the French leader (Groupe Brunet) for lack of available human and financial resources to achieve the prototype implementation.

In summary, the aim of the project was to deploy and market micro-greenhouses by taking advantage of existing autonomous energy and water production/management solutions. The idea was to develop a new product (intelligent connected greenhouse in kit form) based on the pooling of knowledge of actors in the field of urban development and circular system for space and Earth-based applications, whose capacities for innovation could be mutually reinforced. With the prospect of industrial outlets for autonomous energy and water production/management solutions, the players involved intended to make the regional economic fabric a reference in the field of autonomous and intelligent habitat. The main objectives were:

- To deploy micro-greenhouse as educational demonstrator, with the support of local authorities to demonstrate an intelligent autonomous ecosystem for healthy food production);
- To commercialize these products in the form of a smart connected greenhouse kit, initially in France and Switzerland, taking advantage of the autonomous solutions for energy and water production/management existing at Zest, a subsidiary of Groupe BRUNET, and ESTEE's know-how in the treatment of pollutants and the nutrient recovery from wastewater;
- In a broader and more distant vision, consider the impact of these micro greenhouses for individual housing or collaborative districts and their impact on wastewater treatment plants; and propose open platforms based on SCIMA prototypes so that other academics, associations and companies can develop new skills and solutions.

The key stages of the project were:

- To target the final format of the greenhouse through a market study, targeting first the urban and mountain areas;
- To manufacture several prototypes of this module of a few square metres that can be combined and assembled;
- To demonstrate a prototype that can be industrialised in a region that meets the needs of a national and international market.

Annex I is composed of the following confidential documents which are provided in separated files:

- Annex I1 - Fiche pré-projet 2014-2020 Programme Interreg V France-Suisse du 04.04.2017 (21 pages);
- Annex I2 - Convention d'utilisation des aides au titre du Programme Interreg V France-Suisse 2014-2020 du 10.01.2018 (12 pages);
- Annex I3 - Example of intermediary deliverables: WP B3 - Projet SCIMA : Rapport de définition du système substrat et irrigation (12 pages).

ANNEX J - ESA study for the assessment of the financial and business potentials of LSS technologies (confidential documents)

Project title: Study for the Assessment of the Financial and Business Potentials of LSS Technologies – ESA AO/1-9556/18/NL/AT

ESA Express Procurement [Plus] – [EXPRO+]

Client: ESA

Collaborators: Leoni Corporate Advisors, ESTEE

Dates: 2019-2020

STUDY FOR THE ASSESSMENT OF THE FINANCIAL AND BUSINESS POTENTIALS OF LIFE SUPPORT SYSTEMS (LSS) TECHNOLOGIES - ESA AO/1-9556/18/NL/AT

FINAL DELIVERY

6th March 2020

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MARCH 2020

Annex J is composed of the following confidential documents which are provided in separated files:

- Annex J1 - ESA AO/1-9556/18/NL/AT - Proposal (50 pages);
- Annex J2 - ESA AO/1-9556/18/NL/AT - Final deliverable (1 table);
- Annex J3 - ESA AO/1-9556/18/NL/AT – Interview grid (91 pages).

ANNEX K - Presentations, publications and press appearance

Selection of performed presentations on ACE:

1. Conférence-débat sur nos possibilités de vivre ailleurs, 22.11.2021, **Cartographie de l'Anthropocène avec Frédéric Ferrer, co-production UNIL-Vidy**, *UNIL, Lausanne*
2. How to attract actors of Circular Economy? (workshop chair) 05.11.2020, **MELiSSA conference 2020 - Current and future ways to closed life support system**, *digital event hosted by UGent*
3. Consolidating the Swiss activities and rationale for ALSS and MELiSSA development, 05.11.2020, **MELiSSA conference 2020 - Current and future ways to closed life support system**, *digital event hosted by UGent*
4. Eco-innovation at the crossroads of terrestrial and space dimensions of Life Support System development, 28.10.2020, **Career event 'Be a Star in ESA's Universe'**, *digital event hosted Swiss Space Center*
5. Artificial Closed Ecosystems for Spatial and Terrestrial Applications: The ultimate Circular Economy (coauteur de la présentation de S. Erkman), 04.07.2019, **11th Conference of Science Journalists**, *Lausanne*
6. Scorpius Prototype 1 - Towards a proof of concept of a closed habitat on-ground demonstration integrating main BLSS functions, 26.10.2018, **European Mars Convention 2018**, *La Chaux-de-Fonds*
7. Convergence and perspectives (coauthor of S. Erkman's presentation), 12.06.2018, **Swiss Space Office Workshop Advanced Life Support Systems - MELiSSA**, *State Secretariat for Education, Research and Innovation, Bern*
8. Human settlement in outer space: relevance for terrestrial sustainability and beyond - Artificial Closed Ecosystems as drivers for eco-innovation on Earth and in Space, 09.11.2017, **Space Settlement Symposium - New Worlds 2017**, *Austin, Texas*
9. Artificial closed ecosystems as driver for eco-innovation - Bioinspired systems put into practice at engineering level, 16.10.2017, **Bioinspired Approaches to Engineering workshop**, *EPFL, Lausanne*
10. Oïkosmos: growing convergence of space and terrestrial research agendas (coauthor of S. Erkman's presentation), 15.09.2016, **ESA conference - Space for inspiration**, *Science Museum, London*
11. Oïkosmos research agenda: relevance of manned interplanetary missions to terrestrial sustainability, 09.06.2016, **MELiSSA workshop**, *UNIL, Lausanne*
12. Presentation of the activities of the UNIL industrial ecology group, and brainstorming on finding topics of mutual interest to MELiSSA and industry, and opportunities for cooperation or knowledge exchange, 02.12.2014, **MELiSSA industry workshop: Closing-the-loop workshop**, *ESTEC, Noordwijk, Hollande*
13. Manned interplanetary missions: Which relevance for terrestrial sustainability?, 04.11.2014, **MELiSSA project 25th anniversary**, *ESTEC, Noordwijk, Hollande*
14. Missions Mars : quelle pertinence pour la durabilité terrestre?, 24.10.2014, **nipconf : #comprendre #tester #partager : les changements technologiques à venir**, *SwissTech Convention Center, Lausanne*
15. Manned interplanetary missions: relevance for terrestrial sustainability - Artificial closed ecosystems as driver for eco-innovation, 02-03.10.2014, **IDYST Doctoral Training Event**, *Trient*
16. Industrial ecology relevance in the framework of MELiSSA assets and expertise, 08.07.2014, **MELiSSA BrainSailing Tour**, *Enkhuizen, Hollande*
17. Relevance of manned interplanetary missions for terrestrial sustainability (coauthor of S. Erkman's presentation), 09.04.2014, **MARS and beyond: ventures to the frontiers of science**, on the occasion of the 30th anniversary of CSEM, *Bern*

18. Les écosystèmes clos artificiels : l'écologie industrielle en conditions extrêmes, 04.02.2013, **Workshop 'L'écologie industrielle, utopie ou nécessité?'**, *Université catholique de Louvain, Louvain-la-Neuve, Belgique*
19. Relevance, potential and limits of scientific ecology in the context of industrial ecology - The case of artificial ecosystem, 16.07.2012, **Gordon research conference on industrial ecology**, *Les Diablerets*
20. Artificial micro ecosystems as life support system: synergies for space and terrestrial research, 30.09.2011, **European Mars Convention 2011**, *Neuchâtel*
21. Manned mission to Mars and the future of a hyperindustrial economy, 20.05.2011, **5th EPFL Space Research Day**, *Lausanne*
22. Engineering closed artificial ecosystems: MELiSSA, the European space agency's life support system for long duration manned mission to Mars (poster), 02.09.2010 **Life Science Symposium,** *EPFL, Lausanne*
23. Relevance, potential and limits of scientific ecology in the context of industrial ecology - The case of artificial ecosystem, 12.07.2010, **Gordon research conference on industrial ecology**, *Colby Sawyer college, NH, USA*
24. Intérêt des écosystèmes artificiels clos pour la recherche et pour des applications terrestres, 11.06.2010, **Journée de la Faculté - Jeunes chercheurs**, *UNIL, Lausanne*
25. Écologie industrielle, avenir du système industriel, et Le projet Oïkosmos: Synergies de recherches spatiales et terrestres, 12.03.2010, **Séminaire du Laboratoire d'energie solaire et de physique du bâtiment**, *EPFL, Lausanne*
26. Le projet Oïkosmos: Synergies de recherches spatiales et terrestres (coauthor of S. Erkman's presentation), 03.03.2010, **Forum des 100, 'Health Valley'**, *Merck Serono, Genève*
27. Perspective of MELiSSA for development of a terrestrial research agenda including space and terrestrial synergies, 14.01.2010, **Séminaire du Département de biologie moléculaire et végétale**, *UNIL, Lausanne*
28. Perspective of MELiSSA for development of a terrestrial research agenda including space and terrestrial synergies, 13.11.2009, **Séminaire du Département de microbiologie fondamentale**, *UNIL, Lausanne*
29. Perspective of MELiSSA for development of a terrestrial research agenda including space and terrestrial synergies. 24.07.2009, **MELiSSA Summer University**, La Vue-des-Alpes
30. Perspective of MELiSSA for development of a terrestrial research agenda including space and terrestrial synergies, 17.12.2008, **Séminaire du Département d'écologie et d'évolution**, *UNIL, Lausanne*

Main publications and press appearance:

1. Recyclage des déchets ou nutrition, la Suisse prépare la survie dans l'espace, 08.12.2020, **RTSinfo.ch (dont la Une)**
2. Conquête spatiale : la survie dans l'espace, 03.12.2020, passage à l'émission 'Tout un monde' de la **Radio Télévision Suisse - La 1ère**
3. Recherche en action - Les écosystèmes clos artificiels étudiés au sein du programme Oïkosmos, 08.07.2016, **geoblog, FGSE, UNIL**
4. Comment les astronautes se préparent à la vie sur Mars, 20.06.2016, **Le Monde**
5. Comment vivre en vase clos au fin fond de l'espace, 12.06.2016, **Le Temps**
6. Avant de coloniser la planète rouge, 05.03.2015, passage to the radio programme 'CQFD' on **Radio Télévision Suisse - La 1ère**
7. Vivre en vase clos en direction de Mars, 27.10.2014, passage to the radio programme 'CQFD' on **Radio Télévision Suisse - La 1ère**

8. @Theodore_Besson parle de Mission Mars…inspiration et sensibilisation au développement durable, 26.10.2014, **Nipédu spécial Nipconf hors série (podcast)**
9. Et si l'aventure d'un voyage vers Mars commençait en Suisse romande…, 24.10.2014, **Le Temps (dont la Une)**
10. Report: Switzerland ideal for Mars simulator, 24.10.2014, **thelocal.ch**
11. Mission habitée sur Mars : pour demain ?, 08.08.2014, passage to the radio programme '2064' on **Radio Télévision Suisse - La 1ère**
12. A. Nussbaumer, P. Zurbruegg, S. Erkman, T. Besson, Building on planet Mars student project, 2013, **Structures and Architecture : New concepts, applications and challenges**, Editeur: Cruz, Paulo J. S., Taylor & Francis Group, London : p.1411-1418
13. Les excréments, source d'énergie?, 14.02.2012, passage to the radio programme 'Les temps modernes', on **Radio Télévision Suisse La 1ère**
14. Recycler pour aller sur Mars, 22.04.2010, passage to the radio programme 'Biosphère' on **Radio Télévision Suisse - La 1ère**
15. Le voyage vers Mars pourrait commencer à Lausanne, 24.02.2010, **L'Hebdo**
16. Déchets de l'espace cherchent recyclage à La Vue-des-Alpes, 22.07.2009, **L'Impartial**
17. Passage à l'émission 'Ciels d'été: objectif Mars', 13.07.2009, **Radio Télévision Suisse La 1ère**