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Modeling and Simulating a Regenerative Life Support System to Understand the Effects of System Interaction on Survivability During Deep Space Missions: An Agent-Based Approach

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Abstract

To enable sustainable long-duration human space flight, regenerative life support systems (RLSS) will be indispensable. Waste materials will need to be processed and transformed back into nutrients for life-supporting ecosystems. MELiSSA (Micro-Ecological Life Support System Alternative) is a well-documented and studied example of such an RLSS, developed by the European Space Agency. The system consists of five interconnected compartments: a crew compartment, an edible plant/algae compartment, and three types of bioreactors. The microorganisms in the bioreactors gradually break down the waste materials of the astronauts and provide the edible plants and algae with their necessary resources. This paper proposes a model of an agent-based system (ABM) of MELiSSA in which the five compartments and their interactions are modeled and implemented using virtual agents that represent humans, plant plots, and bioreactors. The model also includes the corresponding mass flows of chemicals. For each type of agent, its properties, behavior, life cycle, and rules of interaction are described. An 'administrator agent' implements 'top-down' rules for overall control where needed. The behavior of each biological agent is modeled according to the expected behavior and main chemical reactions within each MELiSSA compartment, as documented in publicly available sources. Rules implemented to describe the complete life cycle of the agents – e.g., growth curves and susceptibility to nourishment deficits – are also included. This 'bottom-up' approach, characteristic for ABM, allows for the emergence of patterns that provide insight into the behavior of the overall system. In addition, the mass flows are made visible as the different chemical compounds are exchanged between compartments. This agent-based system of MELiSSA is, in fact, a simulation platform with which the behavior of the cycle as a whole, down to its individual agents, enables exploration of the robustness of the system and the impact of stressors on survivability. A series of simulation experiments has been set up for this purpose. Two types of stressors are used in these experiments. First, stochastic outputs from at least one of the compartments, beginning with the crew compartment. Second, environmental stressors, more specifically cosmic radiation causing loss of metabolic functionality and particle impact causing catastrophic failure of parts of the life support system. This research is part of the E|A|S (Evolving Asteroid Starships) project by the DSTART team at Delft University of Technology. The project entails conceptual research on interstellar travel, including onboard regenerative ecosystems.

Keywords: Biological life support; Regenerative life support system; Mass flow; MELiSSA; Simulation; Agent-based modeling

1. Introduction

1.1 E|A|S (Evolving Asteroid Starships)

The hostile environment of interstellar space and its unpredictable impact require a new approach to spacecraft design, one that differs radically from current paradigms in aerospace engineering. In the E|A|S (Evolving Asteroid Starships) project a design solution is proposed in which a starship is attached to a C-type asteroid and whose architecture consequently grows and evolves over time (Fig. 1). The starship mines resources of the asteroid, while at the same time using the asteroid as a shielding structure against frontal impacts. The extracted raw materials are refined and then used for the gradual expansion of the starship's 3D manufactured architecture, both inside and outside the asteroid. The refined materials are also used for the cultivation of an onboard regenerative ecosystem that enables long-duration operation. The goal of the project is to create a hybrid computer model in which different mission scenarios can be explored. [1]

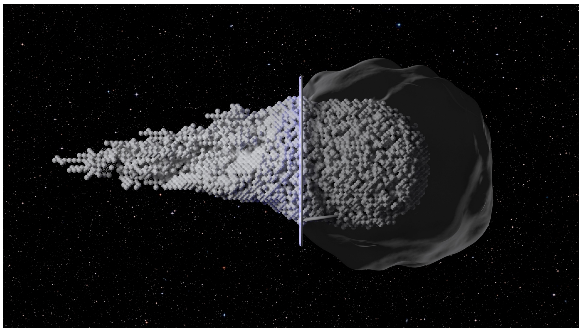

Fig. 1. Artist impression of the E|A|S (Evolving Asteroid Starships) concept combining asteroid mining and space-based 3D manufacturing. 3D modeling by Nils Faber.

1.2 Regenerative life support for human interstellar exploration

The integration of an onboard regenerative life support system is imperative to enable long-term survival of a human crew during an interstellar mission [2]. Because of limited onboard supplies and lack of resupply possibilities it is important to avoid waste and enable the recycling of every molecule. This can be achieved by establishing an artificial ecosystem in which a sequence of organisms breaks down waste products, finally resulting in fresh crops that provide food and oxygen for the human crew. The MELiSSA (Micro-Ecological Life Support System) project from the European Space Agency is a concept for such an artificial ecosystem (Fig. 2). It was inspired by terrestrial aquatic ecosystems and breaks down human waste (CO2, sweat, urine, feces) through a series of bioreactors, algae and higher plants. The entire system is organized into 5 compartments: the human crew; 3 types of bioreactors with respectively thermophilic anaerobic bacteria, purple bacteria and nitrifying bacteria; and a food production compartment with edible micro-algae and agricultural crops [3].

1.3 Impact of the interstellar medium on an onboard regenerative life support system

One of the major challenges in human interstellar exploration is the impact of the interstellar medium on an onboard regenerative ecosystem and its constituent organisms, including the human crew. This can be divided into two main challenges: radiation and impacts of dust particles.

1.3.1 Interstellar radiation

Galactic cosmic rays (GCR) represent the main source of radiation in interstellar space. The density of GCR increases when leaving the heliosphere and is assumed to be isotropic once interstellar space is reached [4]. Hassler et. al. have analyzed the GCR dose on the Martian surface with its applicability to a human mission on Mars. They concluded that at a depth of 3 m, the GCR dose-equivalent rate is 2.9 mSv/year [5]. Therefore, it can be inferred that astronauts on board of the asteroid starship would be significantly more protected if they are living within the hollowed out asteroid (having a density of at least 2.8 g cm^{-3}, the same as the estimated rock density by Hassler et. al.) [5]. However, real levels of GCR in interstellar space are not known because no direct measurements have been made yet. Also, because of the problem of secondary radiation, the actual protective qualities of regolith (or asteroid material) might be overestimated and experienced radiation levels might be higher [4]. And because of the limited space inside the hollowed asteroid, part of the starship's architecture will have to be developed outside of it (as illustrated in Figure 1), exposing it directly to the interstellar medium. It is therefore assumed that part of the regenerative ecosystem and human crew will be, at least intermittently, exposed to higher levels of radiation than experienced here on Earth.

In recent MELiSSA research, different results have been published about the effect of radiation on the organisms. During relatively short exposure times (ranging from a number of days to less than a month), microorganisms do not seem significantly affected by radiation. Illgrande et al. investigated the effect of 7 days exposure to 2.8 mGy, a dose 140 times higher than normal conditions, on Rhodospirillum rubrum (CII) and Nitrosomonas (CIII) while in orbit on board the ISS. The results gave no difference between the control group on Earth and the test group at the ISS [6]. Badria et al. tested the radiation resistance capacity of the cyanobacterium Arthrospira (CIVa). This research showed that the bacteria can survive up to 6.4 mGy (25 days) [7]. However, there's many studies that indicate that mutation rates go up in the presence of radiation [8,9]. Moreover, the combined effect of microgravity and space radiation activates defense mechanisms that might affect microorganism's behavior drastically [8]. This could lead to unexpected dynamics in the MELiSSA loop. Cortese et al. provide a good overview of the different effects of radiation on living organisms in an extensive review paper [9].

NASA has strict limits on the amount of radiation astronauts can be exposed to. Other space agencies follow the NASA standard as well. The limit varies based on the gender of the astronauts, their age, if they are smokers or not and assumes no previous occupation in radiation environments. The limit is expressed in Sievert (Sv), the weighted equivalent of a joule of radiation energy absorbed in a kilogram of tissue. The highest effective dose an astronaut can

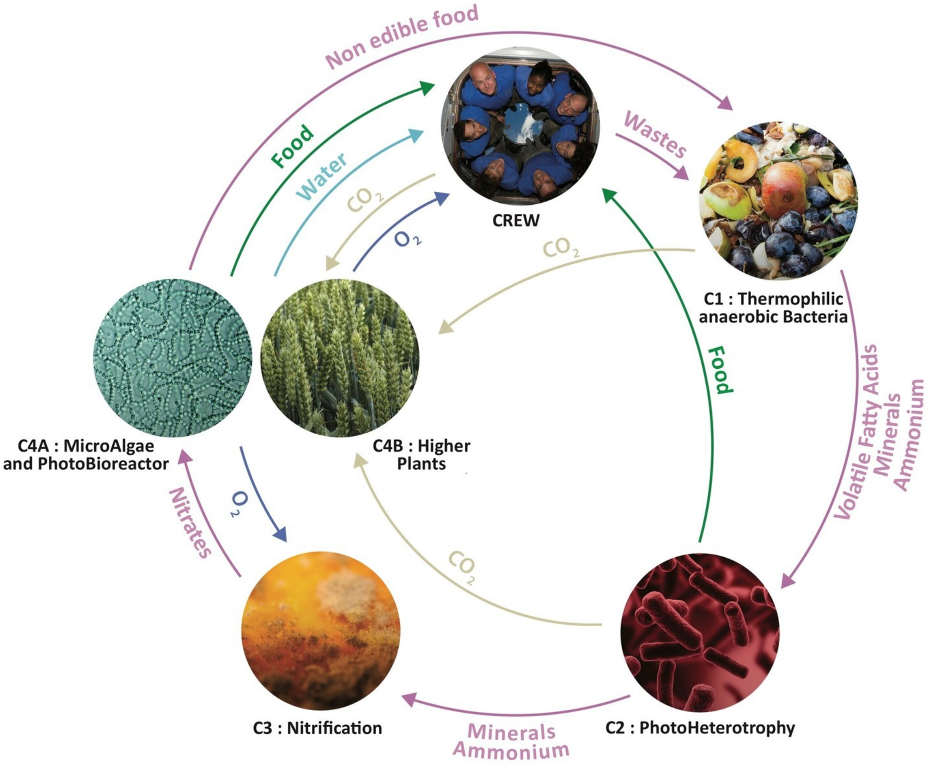

Fig. 2. The MELiSSA loop showing its five compartments and the different mass flows in the system. Diagram by the MELiSSA Foundation.

withstand in a 1-year mission is 1 Sv. This results in a maximum probability of 3% that astronauts will develop a fatal type of cancer, with a 95% confidence level [10]. Cucinotta et. al. developed a model based on the NASA standard and estimated the number of safe days in space to be 300 days for females and 400 days for males [11]. The model assumes the spacecraft is within the heliosphere and has an aluminum shield of 20 g/cm^2 [11]. This signifies that beyond the heliosphere more significant shielding will have to be added. But due to limited material resources, it might not be possible to lower radiation levels to those on Earth and the crew might still (intermittently) experience higher radiation levels.

1.3.2 Interstellar dust and particles

Another important aspect of the ISM are particles. Dust grains beyond 50AU (0.00079 ly) are most probably larger than 1 μm [12]. However, despite their size, they might significantly damage the starship because of high impact velocities. Their densities are known for the Local Interstellar Cloud (LIC) where the Sun is located. That density is 7.5 x 10^{-15} cm^{-3} [12,13]. It is important to note though, that only two probes have reached beyond the edge of the heliosphere (Voyager 1 and 2) and that in general little is known about specific properties of interstellar space. The densities of dust particles in the G cloud for example, where Alpha Centauri is located, can only be estimated. The real values might significantly differ from expectations and can only be established once in situ measurements are made. Apart from dust grains, there's also smaller particles present in interstellar space such as protons, alpha particles and electrons. Because of high impact velocities these might also have a significant impact [13,14].

1.4 Modeling the MELiSSA regenerative life support system

The goal of this paper is to create a model of the entire MELiSSA loop as a tool to understand the effects of system interaction and the impact of the interstellar medium on long-term survivability. This paper describes the current version of the model and discusses some first preliminary results.

The MELiSSA Foundation regularly publishes an updated list of peer-reviewed MELiSSA research papers [15]. Holistic models of the MELiSSA loop have been developed and improved since the beginning of the MELiSSA project in 1988 [16]. However, when reviewing all published MELiSSA models and results, they could not readily be used for our research objectives. General issues were the fact that the stoichiometry was not 100% closed, the experiments were run in controlled instead of fluctuating environmental conditions, and no long-term tests and simulations were published. Dussap et al. [17] were the first to find a solution for the mass balances. Four elements C, H, O and N are traced in this loop. However, if we look at the stoichiometry in this model it is assumed that all lipids consumed by the astronauts are oxidized and no traces of lipids are found in the feces. Simulations with this model were run under steady state conditions. Lasseur et al. describe in their paper of 1996 a proposal to close the C cycle of the system [18]. The focus of this research was recycling of waste streams of the crew. The elements C, H, O, N, S, P are all integrated, and conceptually 99,5% of N is recovered. However, the stoichiometry is not mentioned which makes it difficult to actually close the loop using mass balance. A paper by Hendricks et al. focused on the recovery of food and oxygen in the MELiSSA loop [19]. Different chemical conversions are described in this article. However, these reflect general conversions, and as a result the stoichiometry cannot be used to conceptually close the loop. And just like in Dussap's previously mentioned paper, feces only consist of fibers, carbohydrates and proteins. Lipids are not taken into account. Farges et al. took a first principles approach to model the MELiSSA loop. The article focuses on developing a hierarchical control strategy for the loop, from the compartment level up to the overall loop [20].

2. Materials and methods

2.1. Agent-based modeling

Since MELiSSA is conceived as an ecosystem it stands to reason to look at tools used in modeling such systems. Moreover, we are looking to model it beyond the features published in literature. We are interested in its long-term stability and robustness when dealing with the possible hazards of long-duration interstellar missions. As such, we need a tool that has the required granularity and the possibility to show us stepwise development of the ecosystem with possible emergent patterns under the aforementioned conditions. Agent-based modelling meets the key needs of our project. On one hand, the focus of the model is on the individual parts of the system or so-called 'agents'. On the other hand, we are interested in any insights we may gain from observing the continuous interaction of these agents over long periods of time and under different stress conditions.

To implement our project, we are using NetLogo (version 6.1.0), a programming language and integrated development environment specifically designed to build agent-based models. It allows for clear and explicit statement of the agents, their parameters, interaction rules and environmental conditions. Plus, it facilitates the tracking of the agents via an intuitive graphic display, showing their states and even spatial displacement.

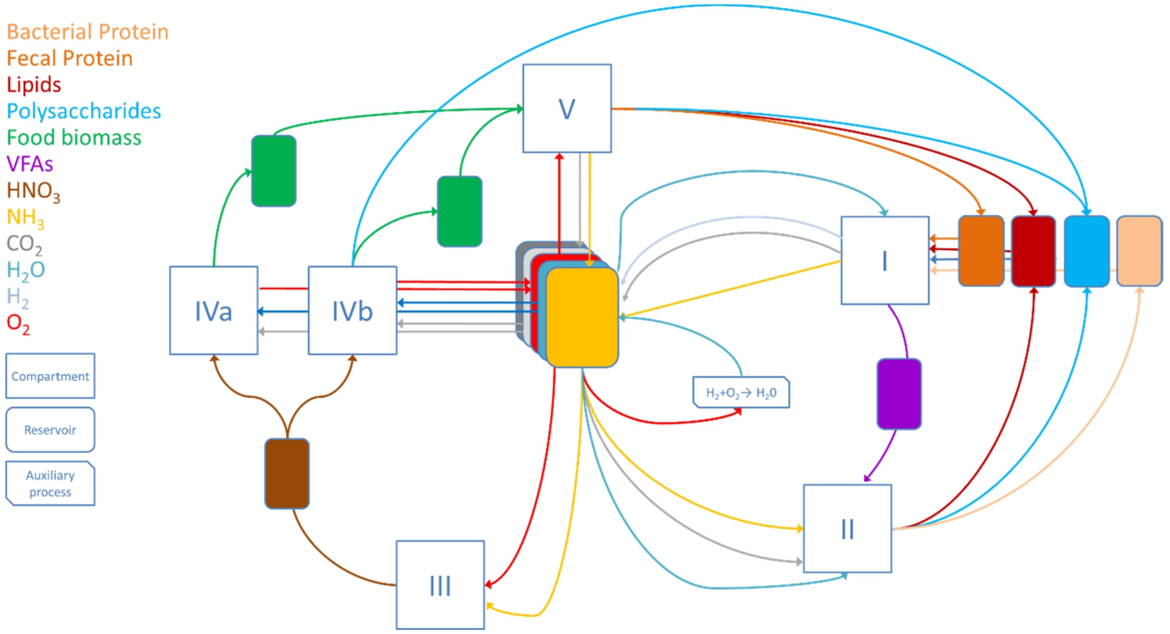

Fig. 3. Adjusted MELiSSA mass flow diagram that was used in the agent-based model. An overview of all specific adjustments can be found in the Materials and Methods section.

2.2. Model assumptions and requirements

2.2.1 Mass flux

The model consists of 6 compartments with agents, several reservoirs for compounds and auxiliary units for additional processes (Fig. 3). All produced compounds are directly stored in their respective reservoir and it is assumed that all agents have full access to these reservoirs. One auxiliary process has been added to the MELiSSA loop for the burning of surplus H_2. Microorganisms of the bioreactors in Compartment I (CI) and Compartment III (CIII) are not taking part in the mass flux. Therefore, we assume these bacteria have no mass. Another difference between our model and published MELiSSA models is that we assume that the surplus of biomass produced in CII is not used as food for the human crew but goes back to CI instead (with a 100% digestion rate).

2.2.2 Stoichiometry

A new stoichiometry of the entire loop had to be constructed. It is crucial that the mass flow is fully closed, and agents transfer molecules throughout the loop without any inconsistencies.

All the molecules in this mass flux are composed of the following elements: carbon (C), hydrogen (H), oxygen (O) and nitrogen (N). Other research also uses only C, H, O and N in their mass flux [17,21]. Other elements such as sulphur (S) and phosphorus (P) are not (yet) taken into account in the agent-based model. The reason is that the S and P loops in MELiSSA are not yet clearly defined. Moreover, it will make modeling even more complex [20,22].

From these elements molecules are being constructed. But the problem is that some substances are difficult to reduce to one single molecule. They consist out of a range of different molecules such as biomass, for instance. To describe this, we make use of macro formulas. In other literature, $C_5H_7O_2N$ is often used as the general formula for biomass. This does not mean that such a kind of molecule actually exists. It is an aggregation of all the constituent molecules expressed as a combination of individual elements.

Another example of simplification in our model is the composition of urine. We're aware there's a wide variety of compounds present in urine [23]. In our model, we consider urine solely as NH_3. The next step in our model development is to describe the composition of urine and the biological conversion of nitrogen in a more realistic manner.

2.2.3 Flow rates, productivities and mass conservation

An average daily caloric need of 2000 kcal/person was assumed. An 'ideal plant' was constructed as an average of 4 different crops (wheat, potato, soybean and durum). The diet consists of 1800 kcal ideal plants and 200 kcal micro-algae (Arthrospira). Using the caloric values of the ideal plant and micro-algae, the amount of biomass that was needed on a daily basis was determined for each. Using these figures, the flow rates throughout the entire loop could be established by starting in CV and working backwards through the entire stoichiometry. The results can be found in Table 2.

Productivities of the different agents can be found in Table 3. The values for CI, CII, CIII and CIVa are based on literature. The value of CIVb is based on the target output of 1800 kcal/day/person. The value of CV is based on the stoichiometry of CV and a total caloric consumption of 2000 kcal/day/person. The size of the bioreactors in CI, CII, CIII and CIVa are based on realistic values used in the MELiSSA project [24]. The number of bioreactors in each compartment was determined according to below formula. The amount of plants in CIVb corresponds to a daily output of 1800 kcal/day. An overview of all figures can be found in Table 3.

$$\frac{Flow\ rate/day}{\frac{Production}{L}/day} = Q \tag{1}$$

and

$$\frac{Q}{S} = B \tag{2}$$

Flow rate: what is needed to keep the loop running with a daily output of 2000 kcal/person
Q: amount of bioreactor liquid needed (L)
S: standard size of a bioreactor (L)
B: number of bioreactors needed

Using the data from Table 1, 2 and 3, the flow conservation rates can be calculated. This is a good way to verify whether there's any inconsistencies in the design of the ecosystem (stoichiometry, number of agents, etc.) The results can be found in Table 4. Flow conservation rates are 100% or very close to that, for all compounds.

Table 1. Stoichiometric equations describing the general C, H, O and N cycles in the MELiSSA loop as used in the agent-based model. The equations were sourced from literature and calculated using a solver built in Excel. The organisms are represented as agents in this model. Their properties and behaviors are described in section 2.3.

Compartment	**Chemical equation**	**Organism**
CI	Bacterial protein $3,2CH_{1.4697}O_{0.34}N_{0.2807} + 2,712H_2O \rightarrow C_2H_4O_2 + 0,1C_4H_8O_2 + 1,3162H_2 + 0.8982NH_3 + 0,8CO_2$ Fecal protein $3,2CH_{1.76O0.239}N_{0.239} + 3,035H_2O \rightarrow C_2H_4O_2 + 0,1C_4H_8O_2 + 2.3H_2 + 0.76NH_3 + 0,8CO_2$ Polysaccharides $3,199CH_{1.667}O_{0.833} + 1,134H_2O \rightarrow 1C_2H_4O_2 + 0,1C_4H_8O_2 + 1,4H_2 + 0,8CO_2$ Lipids $C_{16}H_{32}O_2 + 13,0278H_2O \rightarrow 6,5278C_2H_4O_2 + 0,6528C_4H_8O_2 + 0,3333CO_2 + 13,3611H_2$	Thermophilic anaerobic bacteria
CII	Volatile fatty acids $50.39C_2H_4O_2 + 5.04C_4H_8O_2 + 25NH_3 + 0.19CO_2 \rightarrow 89.06CH_{1.4697}O_{0.34}N_{0.2807} + 18.33CH_{1.667}O_{0.833} + 0.86C_{16}H_{32}O_2 + 63.98H_2O$	Rhodospirillum rubrum
CIII	Nitrification $NH_3 + 2O_2 \rightarrow HNO_3 + H_2O$	Nitrosomonas and Nitrobacter
CIVa	Carbon fixation $5CO_2 + 3H_2O + HNO_3 \rightarrow C_5H_7O_2N + 7O_2$	Arthrospira
CIVb	Carbon fixation $5CO_2 + 3H_2O + HNO_3 \rightarrow C_5H_7O_2N + CH_{1.667}O_{0.833} + 7O_2$	Ideal plant
CV	Consumption $2.71C_5H_7O_2N + 4.41O_2 \rightarrow 4.20CH_{1.76O0.239}N_{0.239} + 1.48CH_{1.667}O_{0.833} + 0.12C_{16}H_{32}O_2 + 5.88CO_2 + 1.70NH_3$	Human crew

Table 2. Calculated flow rates in the agent-based model. Biomass is expressed in dry weight. The calculation approach is described in section 2.2.3.

Compartment	**Products**	**gram/day/6 pers**
CI	Acetate: $C_2H_4O_2$ Butyrate: $C_4H_8O_2$ Ammonia: NH_3 Carbon dioxide: CO_2 Hydrogen: H_2	8679 1273 1324 4397 436
CII	Bacterial protein: $CH_{1.4697}O_{0.34}N_{0.2807}$ Polysaccharides: $CH_{1.667}O_{0.833}$ Lipids: $C_{16}H_{32}O_2$ Water: H_2O	5840 1421 631 3306
CIII	Nitric acid:HNO_3 Oxygen: O_2	1025 293
CIVa	Food (edible algae biomass): $C_5H_7O_2N$ Oxygen: O_2	400 792
IVb	Food (edible plant biomass): $C_5H_7O_2N$ Polysaccharides (non-edible biomass): $CH_{1.667}O_{0.833}$ Oxygen: O_2	1440 1440 4557
CV	Fecal protein: $CH_{1.76O0.239}N_{0.239}$ Fecal polysaccharides: $CH_{1.667}O_{0.833}$ Fecal lipids: $C_{16}H_{32}O_2$ Urine (ammonia): NH_3 Carbon dioxide: CO_2	528 240 192 174 1552
Auxiliary	Water: H_2O	3898

Table 3. Overview of the number of agents in each compartment based on the productivity and size of each agent, calculated according to formula (1) and (2). Biomass (and feces) productivity values are based on literature or calculated. Further details can be found in section 2.2.3.

Compartment	**Number of agents**	**Productivity**	**Size**	**Nutritional value**
CI	40 bioreactors	6000 mg VFAs/L/day	100 liters	
CII	150 bioreactors	2122 mg biomass/L/day	25 liters	
CIII	17 bioreactors	8740 mg nitrates/L/day	7 liters	
CIVa	20 bioreactors	7990 mg biomass/L/day	100 liters	6 x 200 kcal
CIVb	100 plant plots	7200 g edible biomass/day	180 plants	6 x 1800 kcal
CV	6 persons	350 g feces/day		

Table 4. Flow conservation rates in the agent-based model based on the figures in Table 1, 2 and 3. A high level of flow conservation is established.

Compound	**Consumed**	**Produced**	**Flow Conservation**	**Delta**
Bacterial protein	5,840	5,840	100.0000%	0.0000
Fecal protein	528	528	100.0000%	0.0000
Polysaccharides	3,101	3,101	100.0000%	0.0000
Lipids	823	823	100.0000%	0.0000
Food (higher plants)	1,440	1,440	100.0000%	0.0000
Food (algae)	400	400	99.9995%	-0.0020
Butyrate	1,273	1,273	99.9997%	-0.0040
Acetate	8,679	8,679	99.9998%	-0.0154
HNO_3	1,025	1,025	100.0012%	0.0121
NH_3	1,498	1,498	100.0001%	0.0010
CO_2	5,949	5,949	100.0000%	-0.0001
H_2O	7,497	7,497	100.0001%	0.0045
O_2	5,349	5,349	100.0000%	0.0000
H_2	436	436	100.0005%	0.0024
Total	37,999	37,999	100.0000%	-0.0017

2.3 Agent design and model implementation

Although all types of agents have a common functionality in that all of them receive nutrients and turn it into a different compound useful for other compartments in the cycle, what the agents do with these nutrients and how nutrient scarcity affects them, is different. Hence, we have defined three distinct types of agents. The bioreactor, plant plot and human agents. All of them share some common parameters, but their behavior is significantly different.

2.3.1 Humans

Overall, humans are the simplest agents in our current model, given that they are the only ones whose metabolism doesn't significantly change over time. Their main state refers to their wellbeing and is only affected by the availability of nutrients for their diet and oxygen for breathing. Lacking in these flows triggers the demise of these agents, which in turn represents one of our stop conditions. If the cycle is not capable of sustaining the life of the human crew then it's a failure.

2.3.2 Bacteria and microalgae

Out of 6 compartments 4 of them are bioreactors that are inhabited by different kinds of bacteria or microalgae. The main difference between the compartments is the size of their bioreactors, and the inputs and outputs. Aside from this, their growth is all modelled after a sigmoid curve over 100 simulation steps. And they are modelled to represent the same behaviors under scarcity of nutrients. In case of a lack of sufficient nutrients, growth stops or is reduced proportionally according to the amount fed to the bioreactor. For scenarios where the lack of nutrients is persistent over time, we allow for the proportional unfed percentage of the bioreactor to remain alive for up to 7 simulation steps. After this long it is assumed the famished organisms die out, reducing the overall population density in the affected bioreactor and hence it's productivity. A second factor that can impact productivity is efficiency. This can for example be lowered through radiation.

2.3.3 Plants

Unlike the other agents, the plants as a whole are the output of the compartment. So, we had to consider not only their growth and the effects of scarcity on them, but also the need to have a continuous ‘production line’ of edible plants, to replenish what was harvested. In order to ensure mass preservation, the sigmoid curve representing the growth of the plants had to be meticulously defined. Every day a plant plot is being harvested, enough to fulfill the needs for 6 persons. This corresponds to an output of 10800 kcal by one plant plot on day 100. The harvest index of the plants is 50%, which means that half of the produced biomass is edible. We reduced the complexity of the plant’s composition to two chemical formulas representing both the edible and inedible parts of the plant: the edible part is described as a general biomass macroformula, while the inedible part is described as 100% polysaccharide.

2.4 Simulation experiments

2.4.1 Sensitivity and policy analysis

A first sensitivity analysis was carried out. The efficiency range for a compartment was gradually increased, while the specific efficiency values were randomly chosen within that range using a Monte Carlo method. The efficiency value indicates how much of the input molecules actually get processed and transformed into output molecules (according to their corresponding stoichiometry). This was done for each compartment, while keeping efficiencies in all other compartments at 1. The efficiency range was gradually decreased from 1.0 to 0.9 in steps of 0.02. Each experiment was run 50 times.

Two policies for dealing with nutrient deficits were used: one without prioritization and one with prioritization. Without prioritization, nutrient deficits are randomly assigned to one or more agents. Since the treatment of agents happens in a random fashion, this means that deficits get randomly distributed over agent populations. With prioritization, CV with the human crew gets prioritized. Remaining deficits get equally distributed over other agents.

The experiments were stopped either because all crew had died or after a maximum of 400 days (under the assumption that the loop would keep on running then).

2.4.2 Impact of the interstellar medium

Preliminary experiments were carried out exploring scenarios with a negative impact of the interstellar medium on all compartments with bioreactors (C1, CII, CIII, CIVa). Both loss of equipment (due to catastrophic particle impact) and radiation were simulated. The impact event happened on day 10 of the simulation. In the case of loss of equipment, a number of bioreactors disappeared from the system. In the case of radiation, an instant 50% decrease of efficiencies took effect in a number of bioreactors, with a slow recovery towards nominal values afterwards. 4 bioreactors were affected in CI, CIII and CIVa, and 6 in CII (because they’re more tightly grouped together).

3. Results

In the sensitivity analysis without the prioritization policy it’s clear that Compartment I (fermentation) is the most sensitive (Fig. 4). All other compartments remain stable under the different tested conditions. With the prioritization policy the loop collapses much more often (Fig. 5). But even at efficiency 1.0 we see a high instability with a lower average hovering around 150 days and a high standard deviation. We see a similar effect of the prioritization policy in the experiments about the impact of the interstellar medium: survival values are generally much lower than compared to the experiments without prioritization policy (Fig. 6 and 7). In the latter, six out of eight conditions are not strongly affected by loss of equipment or radiation and the system seems quite robust.

4. Discussion

Counterintuitively, introducing a policy that prioritizes humans and equally distributes nutrient deficits has a negative impact on the survival of humans. But when looking at sensitivity analysis results this actually makes sense. It is Compartment I (fermentation) that is most sensitive after all, and consequently this is probably the compartment that should get prioritized to ensure a more robust system. Prioritizing Compartment V might in fact be the worst possible policy precisely because it is the furthest removed from the most sensitive compartment. Further experiments will shed more light on this.

When we look at the (preliminary) experiments exploring the effects of loss of equipment and radiation, the system seems to be relatively stable. However, much more experimentation with stronger damage levels is needed to get a better picture of the system’s behavior under adverse circumstances in interstellar space.

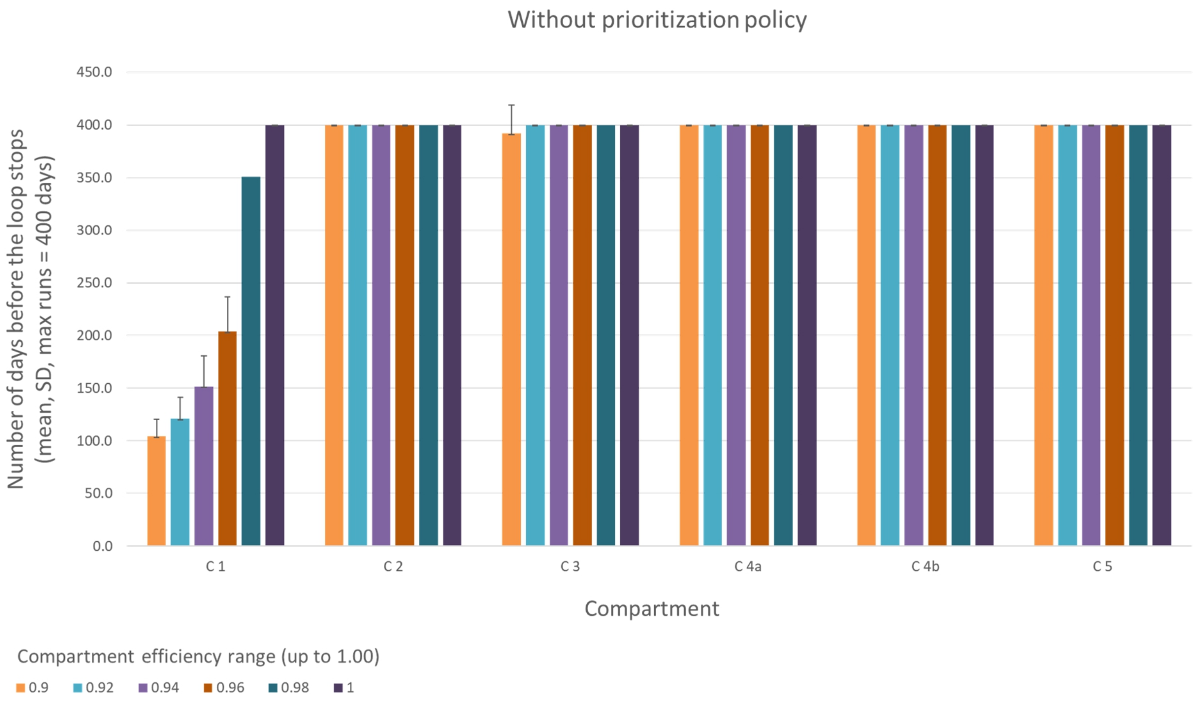

Fig. 4. Sensitivity analysis, without prioritization policy (details in text). The X axis indicates experiments with different compartments. The Y axis indicates the number of days the human crew kept surviving. Experiments were run for a maximum of 400 days. Each simulation experiment was run 50 times. Standard deviations are indicated.

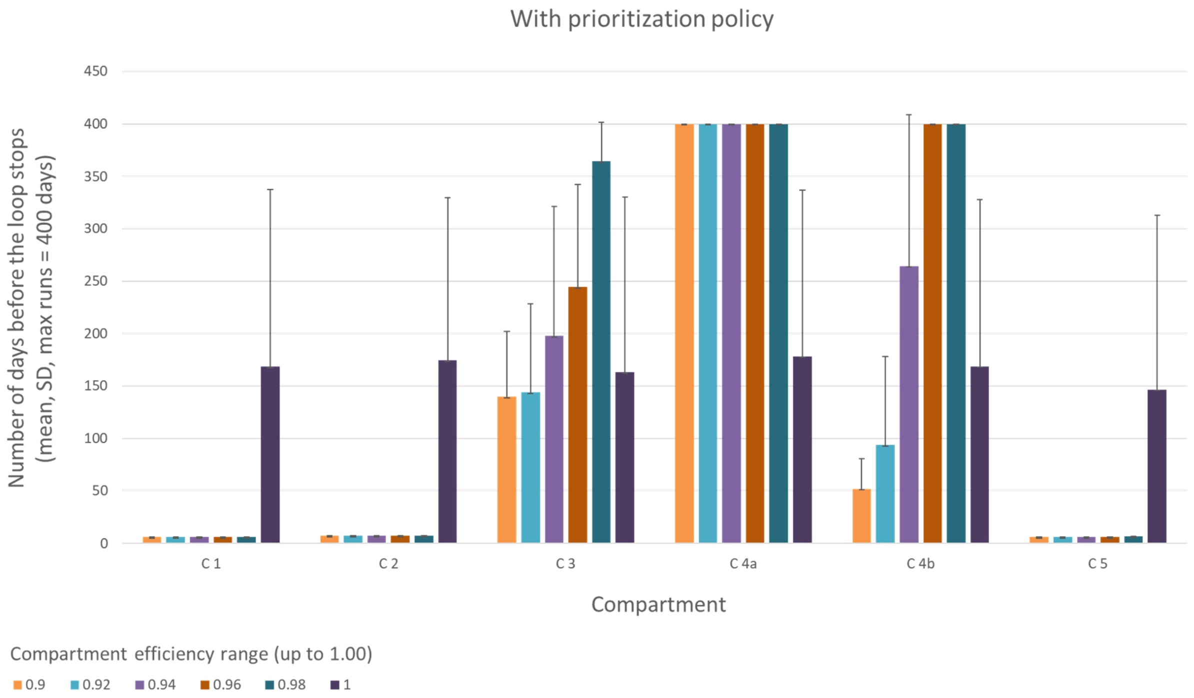

Fig. 5. Sensitivity analysis, with prioritization policy (details in text). The X axis indicates experiments with different compartments. The Y axis indicates the number of days the human crew kept surviving. Experiments were run for a maximum of 400 days. Each simulation experiment was run 50 times. Standard deviations are indicated.

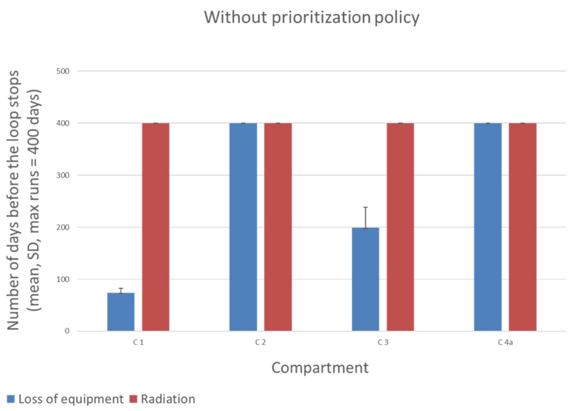

Fig. 6. Preliminary experiments showing the effect of a loss of bioreactors or temporarily reduced efficiencies in bioreactors due to radiation (without prioritization policy, more details in text). The X axis indicates experiments with different compartments. The Y axis indicates the number of days the human crew kept surviving. Experiments were run for a maximum of 400 days. Each simulation experiment was run 50 times. Standard deviations are indicated.

5. Conclusions

The main conclusions of this study can be summarized as follows:

- A stable agent-based model was created based on the MELiSSA loop that can be used to explore the behavior of the entire system under different circumstances (e.g. increased stochasticity), and to investigate the impact of different policies regarding the management of the mass flows.
- First results indicate that Compartment I (fermentation with thermophilic anaerobic bacteria) is most sensitive to increasing stochasticity.
- In almost all compartments a reduced longevity was observed when using a policy that uses prioritization. Adjusting the prioritization scheme might generate better results (e.g. prioritizing the most sensitive compartment).
- In the radiation experiment recovery of all compartments was observed in the absence of a prioritization policy.
- In the loss of equipment experiment recovery was only observed in half of the compartments in the absence of a prioritization policy.
- With a prioritization policy, all compartments in both the radiation and loss of equipment experiments died out after a number of days.

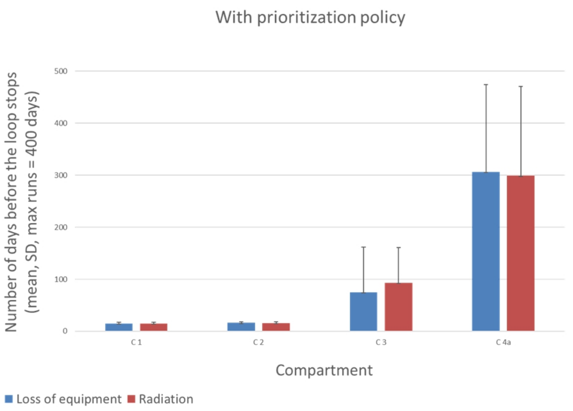

Fig. 7. Preliminary experiments showing the effect of a loss of bioreactors or temporarily reduced efficiencies in bioreactors due to radiation (with prioritization policy, more details in text). The X axis indicates experiments with different compartments. The Y axis indicates the number of days the human crew kept surviving. Experiments were run for a maximum of 400 days. Each simulation experiment was run 50 times. Standard deviations are indicated.

Based on the current results, the next steps of this research involve:

- Using increased degrees of freedom by combining increased stochasticity ranges concurrently in different compartments.
- Expanding the range of efficiencies to stochastically sample from (beyond 0.9-1.0).
- Exploring a wider range of different policies: different prioritization schemes, dynamic adaptive policies, etc.
- Expanding the range of the environmental impacts (radiation, loss of equipment).

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