Effects on ECLSS Behavior caused by the Start-up of a Food Production Facility

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In the next decades humans will take on the challenges of venturing to the Moon, Mars and other planetary bodies in our solar system. The farther out and the longer the crewed missions get, the more effective is recycling of resource to provide life support for the humans travelling. One aspect is the production of food on-site during the mission to greatly reduce the resupply need from Earth. The cultivation of plants hereby is the preferred way. Plants do not only provide a large variety of food, but also consume the carbon dioxide exhaled by the crew and produce oxygen. The cultivation of plants in a closed environment is challenging, but recent experiments on Earth and on-board the ISS have shown the feasibility of such a system. Another aspect of plant cultivation in a crewed spacecraft or habitat is the influence of the crops on the ECLSS. Food production is only possible, when the plants are provided with the resources and environment necessary to thrive. Providing these resources in sustainable way means that the greenhouse subsystems are interconnected with the ECLSS. Consequently, the cultivation of plants has, depending on the amount of crops grown, a significant impact on the ECLSS (e.g. on the dimension of certain systems like the water recycling). This paper presents the results of a dynamic simulation of an ECLSS with an integrated greenhouse for crop cultivation. The focus lies on the start-up phase of this facility, because until the steady-state production is reached the impact of the greenhouse on the ECLSS is changing constantly and therefore the ECLSS has to cope with that. The simulations show that the startup of the greenhouse after the crew arrival with staggered sowing performs best, because this scenario has the best system behavior and does not need additional automation equipment and procedures for sowing and harvesting.

I. Introduction

The implementation of food production through plant cultivation into a space life support system is envisioned to greatly reduce resupply from Earth[1–3] and improve living conditions for humans on long duration space missions[5]. Such space greenhouses cannot only produce fresh food on-site, but also consume the carbon dioxide produced by the crew and produce oxygen for the astronauts or other processes. Consequently, having a space greenhouse incorporated with other technologies (e.g. physical-chemical systems) into a hybrid life support system has many interconnections with those systems and the crew. This means that the plant cultivation is also affecting all those systems due its production and consumption of resources. Depending on the cultivation area and the amounts of plants grown, the greenhouse is going to have a large impact on the life support systems' behavior and resource balance. Simulations of a hybrid life support system have shown that the impact of the greenhouse on the life support system dynamics is substantial when the plant cultivation facility is designed to contribute (~65% of daily calorie intake)[4].

A critical phase for a hybrid life support system is the startup of a plant cultivation facility[6]. The startup phase here means the period from the seeding of the first plants until the greenhouse reaches its production equilibrium. The production of a greenhouse is never going to be constant, but after some time the production rate stays within a certain, nominal, range. This is meant with equilibrium here. The time until equilibrium depends on the chosen crop species and on the production schedule. For the following descriptions the startup phase is defined by longest growth cycle of the implemented crop, which is white potato with 142 days. This paper describes the results of simulations executed to understand the hybrid life support system behavior during the startup phase of a greenhouse that produces 65% of the daily calorie intake of a crew of six astronauts in a Moon or Mars surface habitat system.

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II. Greenhouse Startup Phase Scenarios Definition

One can define four different startup scenarios. Depending on the time and the way the crops are sown, see Figure 1. The scenarios are clustered depending on when the greenhouse starts operation with respect to the arrival of the crew. In the post-arrival of crew startup scenarios the greenhouse is turned on after the crew has arrived at the habitat. The pre-arrival of crew scenarios require an autonomous or remote-controlled greenhouse startup, because the crew has not yet arrived at the habitat. There are two variations for both categories. The sowing simultaneously option means that all plants are sown together at the same time. The sowing staggered option has a distinct production schedule with the plants of each compartment being sown at a specific time.

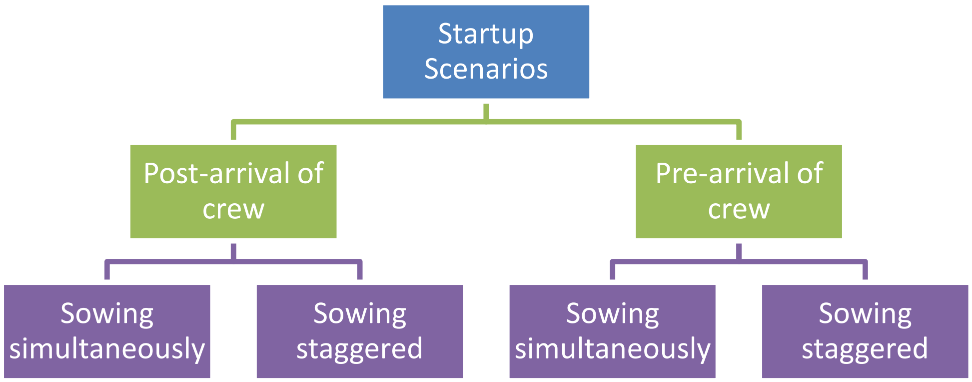

Figure 1. Overview of simulated startup scenarios.

III. Method

The investigations of the impact of the startup of a plant-based food production facility on a hybrid life support system were performed using an existing system dynamics model[4]. This model consists of different components to simulate the crew, physical-chemical life support systems, the habitat and the greenhouse system, see Figure 2. The model of the latter is based on the Modified Energy Cascade (MEC) crop production model[7–10]. This model can simulate the inputs and outputs of nine different crops depending on the environmental conditions (e.g. carbon dioxide concentration, illumination).

The greenhouse startup scenario simulations were run assuming a six-person crew living for 500 days in a Moon or Mars surface habitat. The greenhouse itself has a cultivation area of 299 m² which is divided into 10 compartments. The cultivation area is distributed among the nine crops to allow a diet with a good balance of fat, carbohydrates and protein. The cultivation area of each crop is shown in Table 1. Soybean is delivers a good amount of protein and fat and has therefore the largest cultivation area.

Table 1. Cultivation area for each of the nine crops.

Dry bean	Lettuce	Peanut	Rice	Soybean	Sweet potato	Tomato	Wheat	White potato
15.17	11.42	31.41	10.41	175.80	3.21	9.12	25.25	5.89

Four different production schedules were implemented to simulate the four different startup scenarios described in the previous section. Figure 3 and Figure 4 show an overview of the production schedules for the four different greenhouse startup scenarios. In these graphs a mission day smaller than zero is used for the time prior to crew arrival, which happens on day zero. In the post-arrival - seeding together scenario all plants are sown on day zero and after a germination period of four days transferred to the greenhouse.

The post-arrival - sowing staggered production schedule incorporates adjustments to smoothen the greenhouse production over the mission duration. Therefore the large soybean compartment has been divided into two smaller compartments with half of the original cultivation area. The two soybean compartments are also offset by 43 days.

The pre-arrival - sowing simultaneously scenario has a scheduled seeding for all compartments on day -142. The day is chosen because of the growth cycle of white potato of 142 days, which is the longest among the implemented crop species. This means that in this scenario the whole startup phase of the greenhouse takes place prior to the arrival of the crew.

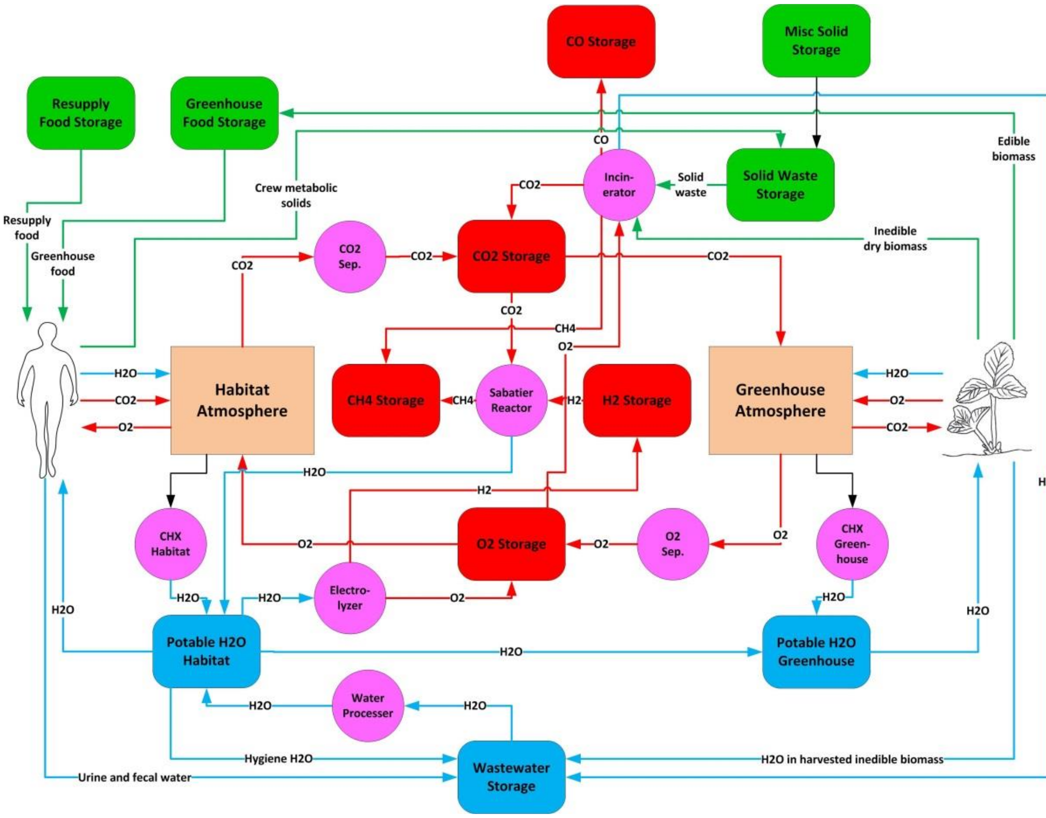

Figure 2. Life support system architecture for the surface habitat simulation scenario. Physical-chemical systems are in purple, liquid mass flows in blue, gaseous mass flows in red and solid mass flows in green[4].

Figure 3. Greenhouse production schedules for the two post-arrival startup scenarios. From top to bottom: Post-arrival - sowing simultaneously, post-arrival - sowing staggered.

Figure 4. Greenhouse production schedules for the two pre-arrival startup scenarios. From top to bottom: Pre-arrival - sowing simultaneously, pre-arrival - sowing staggered.

For the pre-arrival sowing staggered simulation case the seeding of the plants is shifted in a way that all compartments can be harvested for the first time on day one. Consequently, the crew can rely on greenhouse food from the first day of their surface mission in both pre-arrival scenarios.

Simulations of the full hybrid life support system were run for all four scenarios. These include the calculation of all major mass flows (e.g. water, oxygen, carbon dioxide, food). The scenarios were run under nominal operation which means no further perturbations (e.g. crop failure, system malfunction) were incorporated.

IV. Results

The life support system of the pre-arrival startup scenarios is not balanced, because the human component is missing at the beginning. This means, that the plants in the greenhouse are the main consumers and producers of resources. The greenhouse is a large carbon dioxide sink during the startup phase, because of the growing biomass binding carbon. Without having the crew producing carbon dioxide for the plants, all the necessary carbon dioxide needs to be provided to the greenhouse from other sources (e.g. imported from Earth or generated in-situ). There are also no solid waste products and almost no inedible biomass to be processed into carbon dioxide that early in the mission. Figure 5 shows graphs of the carbon dioxide storage behavior for all four startup scenarios. While the post-arrival scenarios can cope with an initial carbon dioxide amount of 50 kg, the pre-arrival scenarios require 700 kg and 800 kg respectively.

The longer overall production time of the greenhouse and the absence of crew in the first 142 days of the mission cause a significant higher overall produced oxygen amount for the pre-arrival scenarios, see Figure 6. The excess oxygen produced in the phase prior to the arrival of the crew could be used to fill up the atmosphere of the habitat to the desired oxygen concentration. This could greatly reduce the amount of oxygen to be imported for the habitat, but on the cost of providing carbon dioxide.

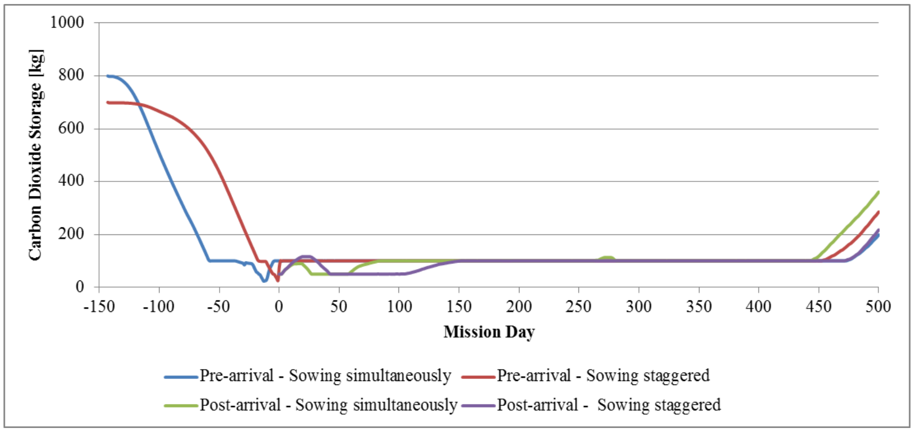

Figure 5. Carbon dioxide storage for different startup scenarios.

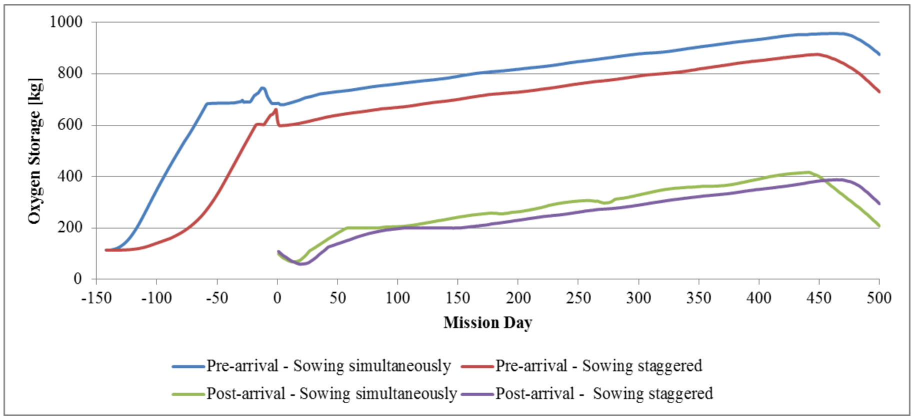

Figure 6. Oxygen storage for different startup scenarios.

This is also clear when looking on the CO_2 consumption rate of the greenhouse in Figure 7 and Figure 8. The pre-arrival scenarios have a high CO_2 consumption rate already before the crew arrives, which stabilizes in a certain range around day -50. The post-arrival sowing simultaneously scenario has low and high spikes in the CO_2 consumption rate, which indicate an imbalanced production schedule. This means, that large amounts of plants are harvested at the same time which causes time spans of very high (>12 kg/d) and very low (<8 kg/d) CO_2 consumption of the greenhouse. Since the oxygen production is coupled to the CO_2 consumption this results in time periods with very low oxygen production. In fact the oxygen production rate drops even below the oxygen consumption rate of the crew for a few days. This is compensated by the implemented buffer tanks, but still a situation that can be avoided with staggered sowing. Here the plant schedule is adjusted in a way that the CO_2 consumption and oxygen production rates of the greenhouse have less intense spikes in either direction. Consequently, the system behavior is smoother.

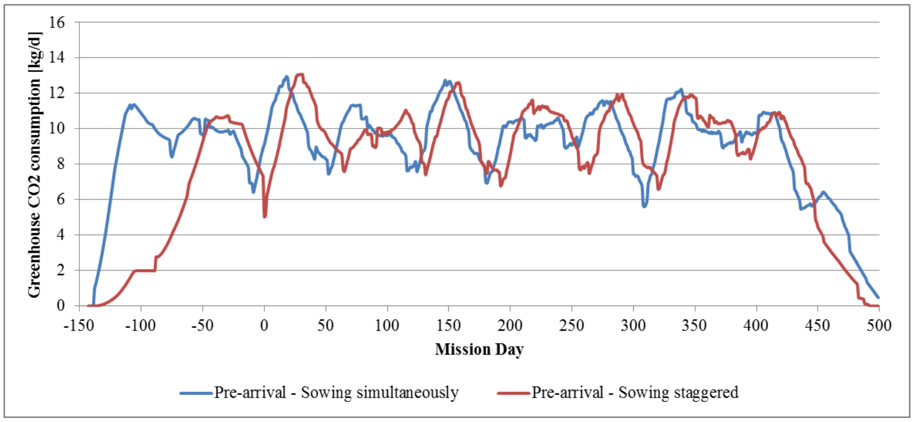

Figure 7. Greenhouse CO_2 consumption for the pre-arrival scenarios.

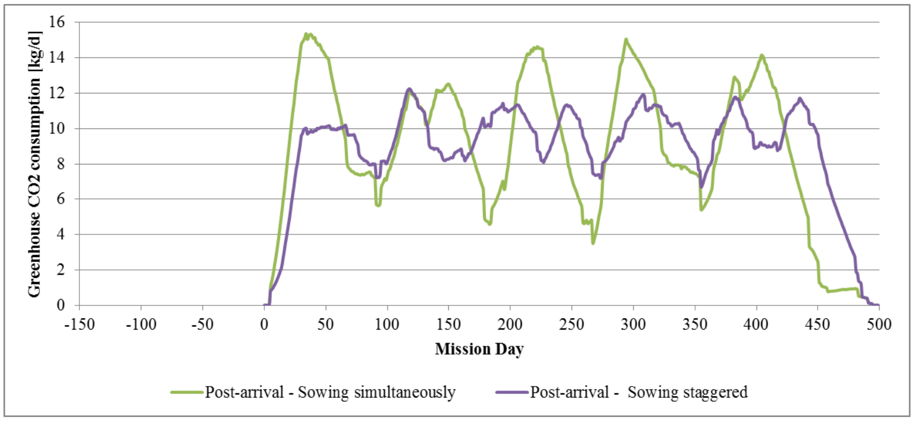

Figure 8. Greenhouse CO_2 consumption for the post-arrival scenarios.

The different production schedules lead to a different amount of produced plant food and therefore to a different amount of resupply food demand. The latter is used to complement the greenhouse food which supplies only roughly 1580 kcal per crewmember per day. Table 2 shows the resupply food consumption for all four greenhouse startup scenarios. The pre-arrival scenarios require less resupply food, due to their overall higher production caused by the earlier startup of the greenhouse. Furthermore, the crew is able to rely on greenhouse food from the first day on in the pre-arrival scenarios and therefore requires much less resupply food.

Table 2. Resupply food consumption in kilograms for different startup scenarios.

Pre-arrival		Post-arrival	
Sowing simultaneously	Sowing staggered	Sowing simultaneously	Sowing staggered
482	554	788	822

The behavior of the water cycle, the activity of the physical-chemical systems and the solid waste cycle behavior are only slightly affected by the different startup scenarios. Consequently, no graphs or tables are shown here.

V. Discussion

The greenhouse startup phase, the phase from seeding to the first harvest of the plants with the longest life cycle, is a critical phase during a mission relying on a hybrid life support system. Four different greenhouse startup scenarios have been simulated. A greenhouse which is setup with plants prior to the arrival of the crew always performs better than a greenhouse that is started after the arrival of the crew in terms of total production of edible biomass. A greenhouse which uses staggered sowing to avoid spikes in the matter flows produces slightly less food than a greenhouse with a simultaneous sowing (assuming the same cultivation area), but the system behavior is smoother and more favorable.

The major disadvantages of the pre-arrival startup scenarios are the need for sophisticated automation for the setup of the greenhouse, the sowing and the harvest of plants. The greenhouse needs to be deployed completely autonomously from its transfer configuration. The greenhouse subsystems need to be implemented in a way, that these are also deploying themselves or can be deployed using remote control. This seems impracticable with all the fluid lines necessary to operate a greenhouse. Developing all these technologies seems to be to cost intense to save a few hundred kilograms of food supply. Automated sowing and harvesting on the other hand is in general of high interest to save the crew valuable working hours. There is also interest of the terrestrial greenhouse industry to implement such technologies. Consequently, there are already projects going on in this direction.

Another disadvantage of the pre-arrival startup scenarios is the need to supply carbon dioxide to the greenhouse because the symbiotic connection between plants and humans is not yet active due to the absence of the crew. While supplying carbon dioxide on Mars can be managed by extracting it from the Martian atmosphere, supplying carbon dioxide or another carbon source on the moon would mean importing it from Earth, because carbon is only present in trace amounts on the Moon. Consequently, the pre-arrival startup does not represent a valid operational scenario for a space greenhouse on the Moon. For a Mars mission it might not make sense to rely on automated sowing prior to crew arrival because the sowing would be performed after the crew left Earth. This means, that if problems with the greenhouse startup arise, the crew is already underway to Mars and cannot be called back and countermeasures need to be performed remotely in order to assure the greenhouse is still operational on crew arrival.

Taking the advantages and disadvantages of all four startup scenarios into account, the post-arrival sowing staggered scenario performs best in general. While this scenario produces the least amount of edible biomass (but only by a small difference), the system behavior is very smooth which is favorable for a hybrid life support system. Furthermore, this startup scenario does not need specialized technologies for automated deployment of the greenhouse and plant handling. There is also no need to supply carbon dioxide, because the crew is already present when plant cultivation inside the greenhouse begins.

Acknowledgments

The content of this paper is part of a PhD thesis submitted to the Technical University Dresden. The PhD position was co-funded through ESA's Networking-Partnering Initiative (NPI).

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