A System Dynamics Model of a Hybrid Life Support System

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The employment of bio-regenerative processes complemented with physical-chemical backup systems and vice versa is thought to have numerous advantages from the perspective of redundancy for the sustained human presence in space or on other planetary surfaces. These so called hybrid life support systems are a concert of many interdependencies and interacting feedback loops, which are challenging to operate in a desired range of set points. Furthermore, the complexity of such systems makes them vulnerable to perturbations. Applying system dynamics modelling to study hybrid life support systems is a promising approach. System dynamics is a methodology used to study the dynamic behaviour of complex systems and how such systems can be defended against, or made to benefit from, the shocks that fall upon them. This paper describes the development of a system dynamics model to run exploratory simulations, which can lead to new insights into the complex behaviour of hybrid life support systems. An improved understanding of the overall system behaviour also helps to develop sustainable, reliable and resilient life support architectures for future human space exploration. The developed model consists of various modules for different life support functions. The greenhouse module simulates plant cultivation. The crew module calculates the inputs and outputs of the crew, while the physical chemical systems module represents a number of life support technologies. All modules are interconnected to simulate a hybrid life support system in a future space habitat.

Nomenclature

BLSS	=	Bio-regenerative life support system
CHX	=	Condensing heat exchanger
ECLSS	=	Environmental control and life support system
MEC	=	Modified energy cascade
MET	=	Metabolic equivalent task
PC	=	Physical-chemical
SD	=	System Dynamics
VPCAR	=	Vapor Phase Catalytic Ammonia Removal

I. Introduction

Environmental control and life support systems (ECLSS) modelling and simulation is important for designing such a system for a future crewed space mission. Over the years various models were programmed and used for ECLSS simulations and some see regular improvements[1]. Most of the existing models only tackle the simulation of physical-chemical life support systems and not bio-regenerative life support technologies (BLSS), which is understandable because current and near-term crewed space mission are going to rely solely on these technologies. For future long-term missions, however, those technologies might not be sufficient. Especially, the lack of food production system is an issue. Therefore, future missions also need to incorporate BLSS for food production and to increase loop closure and redundancy. However, BLSS technologies are still in an early development stage and cause

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a number of additional challenges when designing an ECLSS. A combination of both kinds of systems into a hybrid life support system could combine the advantages of both systems while mitigating their disadvantages. The first step for investigating this hypothesis is a model that can simulate such systems.

This paper presents an exploratory ECLSS model which can simulate such hybrid life support systems. The model incorporates a habitat including crew, physical-chemical technologies and a greenhouse. The purpose of the model is to simulate a wide range of mission conditions and parameter settings in short time in order to explore the system behavior of such a hybrid system. Therefore, the system dynamics approach was chosen for developing the model.

II. System Dynamics

A. Definition and history

System dynamics (SD) can be understood by defining a system as:

> *'A set of elements or parts that is coherently organized and interconnected in a pattern or structure that produces a characteristic set of behaviors, often classified as its function or purpose.'* [2]

and dynamics as:

> *'The behavior over time of a system or any of its components.'* [2]

Ford[3] defines SD as:

> *'a methodology for studying and managing complex systems that change over time. The method uses computer modeling to focus our attention on the information feedback loops that give rise to dynamic behavior.'*

He also quotes another popular definition by Coyle[4]:

> '*System dynamics is a method of analyzing problems in which time is an important factor, and which involves the study of how a system can be defended against, or made to benefit from, the shocks which fall upon it from the outside world.'*

The origin of SD lays in the early works of Jay Forrester in the 1960s at the Massachusetts Institute of Technology. He suggested utilizing methods from feedback control theory to investigate industrial systems[5]. Later the same ideas were applied to the periodic population growths and declines of large cities in the United States[6]. He described a city as a system of industrial and residential areas and people interacting with each other. The study was intended to advise city planners.

Some years later in 1972 the SD approach became popular when the Club of Rome, a non-profit think tank consisting of internationally renowned characters from diplomacy, science and economics, published the report 'The Limits to Growth'[7]. The study investigated the consequences of the raising growth in human population and industrial production. The results were broadly discussed all over the world, because they showed a worldwide collapse of the industrial system and the environment around the year 2100. The world would not sustain unlimited growth of population and industry forever. By altering parameters within the SD model the study authors found out, that stability in economy and ecology is feasible. However, the impact of a certain change or decision greatly depends on the moment they are made.

Since 'The Limits to Growth', SD is used in more and more research fields. Typical applications are the classical SD fields of economics, urban dynamics and models of the development of the world[8]. In recent years SD is also used in investigating climate change[9] and other environmental systems[10]. Modeling of biological systems[11] and health systems[12] is possible. Studying the behavior of ecosystems by utilizing System Dynamics is also feasible and can lead to surprising insights. Typical ecosystem models are predator-prey models (e.g. the overshoot of the Kaibab deer population)[3], Conway's Game of Life and Daisyworld[11].

B. Software

Ford[3] has done an extensive review of different software tools to develop SD models. He makes a comparison made between the widely used spreadsheets with special SD software (Dynamo, Stella, Vensim, Powersim and Simile), with multipurpose modeling software (Simulink, GoldSim) and with individual-based modeling. Based on this analysis and extensive testing of different software packages, the model described in this paper was developed using the program Stella Professional (https://www.iseesystems.com/).

C. Building blocks

System dynamics models are built with only five components: stocks, flows, sources/sinks, converters and interrelationships. By combining these components in different ways, various system behaviors can be modelled. Table 1 gives a short description of each component and the symbols used in the software tool Stella Professional.

A stock is the part of a system where something you can see, feel, count or measure at any given time is accumulated. This accumulation can involve physical material, but also information. Examples for a stock are water in a tank, money in a bank account or the amount of knowledge about a given situation[2].

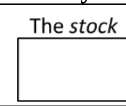
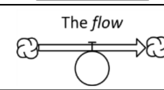
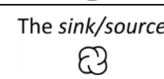
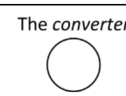
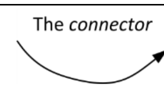
Flows are the tools to change the amount of material or information contained in stocks. They can be inflows, filling the stocks or outflows, depleting stocks over time. Typical flows are births and deaths, purchases and sales, growth and decay[2]. Sources and sinks show flows across the boundary of the system. Whenever there is a source or sink in the model the system is called an open system. Models of closed systems on the contrary do not contain any sources or sinks[3].

Converters are used to direct the flows and stocks through defining limits, demands and other parameters. They influence the rates at which flows run and stocks change.

Connectors link the different blocks of the model with each other. While flows always have to be connected to stocks, interrelationships can be used to connect converters with stocks and flows. Connectors can also display interrelationships between stocks and flows.

In addition to the basic buildings blocks, the software tool Stella Professional (used for this model) offers a number of advanced buildings blocks. Those are implemented to ease the construction of models. The advanced building blocks combine a certain combination of basic buildings and mathematical functions. They can be then directly integrated into to the model, making it easier to construct and clearly arranged models. One such advanced building block that is used across the described model is the module. A module in this case means a part of the model that contains a set of mathematical operations to simulate a certain part of the overall system. Modules can also be run separately from the overall model, which is useful to test certain model functionalities.

Table 1: The five building blocks of System Dynamics models[10].

Name	Short Description	Stella Symbol
Stock or reservoir	A component of a system where something is accumulated. The contents of the reservoir may go up or down over time.	
Flow or process	Activity that determines the values of reservoirs over time.	
Source and sink*	Display flows across the boundary of the system (open system).	
Converter	System quantity that dictates the rates at which the process operate and the reservoir change.	
Connector	Defines the cause-effect relationships between system elements.	

* Explained according to[3].

III. Description of the Model

A. Overview

The model described in the following chapters is organized in modules and sub modules (not to be confused with actual physical modules like those of a space station). The root model contains the six main modules of the model: the crew model, the physical-chemical systems, the greenhouse model, the gases layer, the liquids layer and the solids layer. All modules are connected to other modules as shown in Figure 1. One should note that the arrows shown in Figure 1 not always represent matter flows, as described earlier these arrows are used to indicate interaction between model components. The interaction can be an exchange of actual matter (e.g. water) but also an exchange of information (e.g. number of crew member).

The crew model module, the physical-chemical systems module and the greenhouse model module represent actual components of a life support system. The three layer modules are managing the interaction between the other modules and represent the habitat. Each layer module is only simulating matter in the same aggregation state, e.g. the gases layer module calculates the mass flows of all gases like oxygen and carbon dioxide.

The three layer approach was pursued in order to improve the graphical representation of the model. Furthermore, the separate module approach allows for simulating parts of the model by only running selected modules. Another approach would have been with a single core module which would contain all formulas now represented in the three layer modules.

The following chapters can only give a brief overview of the different model parts. The model itself is relatively complex and explaining every component and formula would go beyond the limitations of a paper. An extensive description and all formulas can be found elsewhere[13].

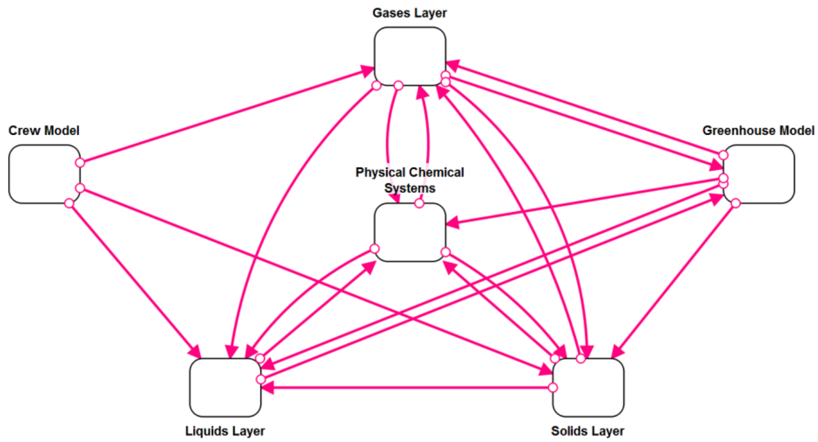


Figure 1: Root model layout in Stella.

B. Gases Layer

The gases layer module calculates the gas flows of the habitat, i.e. mainly oxygen and carbon dioxide, but also hydrogen, methane and carbon monoxide. Each of the gases has its own stocks and flows which are calculated and controlled by inputs from the other modules of the root model. The module is divided into six frames with the core of the layer in the middle (black frame), see Figure 16 in the Appendix. The interfaces to the crew model are on the left side (orange frame), the interfaces to the greenhouse model on the right side (green frame) and the interfaces to the physical-chemical systems in top mid and bottom (purple frames). The bottommost frame is used to convert the concentration of oxygen and carbon dioxide, which are in kilograms for the mass flow calculations in and around the core module, into percent for oxygen and parts per million for carbon dioxide.

C. Liquids Layer

The Liquids Layer module manages all water reservoirs and flows of the habitat. This includes the potable water, the wastewater and the water bound in the crew and the living plants. The water present as humidity in the habitat and greenhouse atmosphere is also calculated by this module. The module is divided into six frames see Figure 17 in the Appendix. The blue frame is the crew frame and calculates the water balance of the astronauts, the potable water storage and the water in the habitat atmosphere. The potable water storage of the greenhouse and the water in the greenhouse atmosphere are managed by the green frame. The water bound in living plants is calculated by the red frame. The two purple frames contain the interfaces to the physical-chemical life support systems. The water in the habitat atmosphere and in the greenhouse atmosphere is calculated in kilograms. The relative humidity requirements are given as percentage. The orange frame converts kilograms to percent of relative humidity based on the habitat and greenhouse volumes.

D. Solids Layer

The solids layer module simulates the solid mass flows of the habitat. This module receives inputs from the crew model, the greenhouse model and the physical-chemical systems module. Outputs are provided to the gases layer, liquids layer and physical-chemical systems module. The module is divided into five frames to distinguish the flows of the different material flows calculated in this module, see Figure 18 in the appendix. The blue frame in the top left corner deals with the crew food. The green frame with the edible biomass produced in the greenhouse. The inedible biomass harvest is treated in the red frame. The orange frame contains the calculations for the crew solid waste and the central solid waste storage stock. The purple frame shows the inputs and outputs from and to the physical-chemical systems.

E. Crew Model

Purpose of the crew model is the calculation of human inputs and outputs depending on the crew composition and the daily schedule of activities. The model is divided into eight sub-modules as shown in Figure 19 in the appendix. Model inputs are parameters concerning the crew composition (e.g. number of crew members, crew member weight), crew baseline values (e.g. waste production rates) and an activity database. The activity database is built on the metabolic equivalent task (MET) principle[14, 15]. This method assigns metabolic energy expenditure to a wide range of human activities based on the human's characteristics (e.g. weight).

The crew model incorporates a crew scheduler which is used to generate an activity schedule for each crew member. Therefore, specific crew member days are setup (e.g. nominal day, leisure day, high-workload day). Different crew member days are then combined to a mission profile for each crew member. The crew mission profile then provides total values for the daily oxygen consumption and calorie demand to the gases and solids layer modules. The crew water demand module calculates the daily water intake of the crew and provides the results to the liquids layer module. The crew solids production module uses the information on the daily water demands to calculate the daily solids production. The misc. crew parameters module contains baseline values not directly related to the human metabolism (e.g. hygiene water demand).

F. Greenhouse Model

The greenhouse model module consists of eight sub-modules, which calculate intermediate parameters or function as input or output interface. Figure 20 in the Appendix shows the setup of the greenhouse model module in Stella Professional. The crop scheduler is used to setup a cultivation schedule for the greenhouse. Therefore, the crop scheduler divides the greenhouse into separate compartments which can vary in cultivation area. Each compartment can house one crop species at a time. The crop scheduler also defines the cultivation cycles (sowing date, harvesting date, etc.) for each compartment, which allows the setting up of a wide range of crop settings inside the greenhouse.

The crop scheduler provides input to the MEC (Modified-Energy-Cascade) crop model[16–19], which is a sophisticated input-output plant model. The crop water accumulator module calculates the daily water accumulation of the plants, which is not part of the original MEC model. The other plant properties module contains an arrayed converter which holds certain parameters such as harvest index, water content in biomass and amount of macronutrients (fat, protein, carbohydrates). In Figure 20 the interconnections between the different sub-modules are shown as they are in the Stella.

G. Physical-Chemical Systems Model

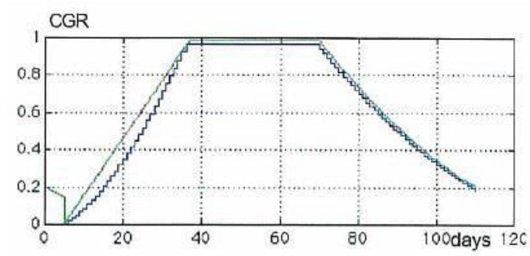
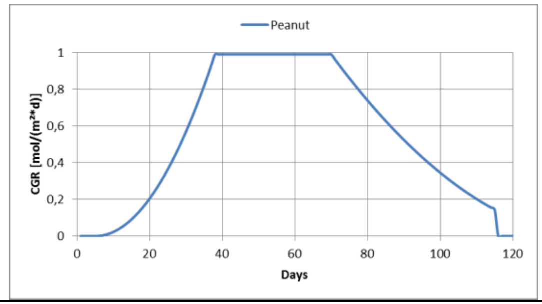
The physical-chemical systems module has no sub-modules like the previously described crew model and greenhouse model, because it contains several individual technologies rather than a complete model. The different physical-chemical technologies are represented by colored frames within the model, see Figure 21 and Figure 22 in the Appendix. Each frame contains only the components necessary to model the behavior of that specific technology and has its own inputs and outputs to the gases, liquids and solids layer of the root model. Figure 21 shows a screenshot from the top part of the physical-chemical systems module as it is implemented. The red frame contains the calculation of the incinerator which is used to recycle solid waste. The blue frame indicates the calculation of an electrolyzer which is used to break water into hydrogen and oxygen. The green frame represents the modelling components for a Sabatier reactor which is used to combine hydrogen and carbon dioxide to methane and water. Figure 22 shows the bottom part of the physical-chemical systems module which contains the calculations for the habitat and greenhouse condensing heat exchangers in the teal frame, the calculations for the Vapor Phase Catalytic Ammonia Removal (VPCAR) in the purple frame, the calculations for the oxygen and carbon dioxide separators in the orange frame and the calculations of the inedible biomass processor in the black frame.

IV. Model Validation

The overall model could not be validated against experimental data, because of the lack of such data in general and specifically for the life support system architecture implemented in the model. However, different parts of the model have been validated independently.

The original MEC plant models are based on experimental data and the model of this paper accurately reproduces the MEC model. The greenhouse model has been verified against the original MEC. Therefore, the values listed by Jones[20] have been used to calculate the crop growth rates for each of the nine implemented crop species. Table 2 shows the crop growth graph for peanut of the original MEC model in the left column and the graph in the right column generated by the model presented in this paper. One can see that the greenhouse model accurately reproduces the original MEC values. The model graph has a smoother look, because more values per time step are being calculated than in the original MEC model. The model has also been validated for the other eight crops. The graphs of the described model all matches those of the MEC model, but only the peanut graphs are shown here.

Table 2: Comparing the output of the original model and its implementation in Stella.

Crop growth rates[20]	Crop growth rates of the described Stella model
Peanut 	

The crew model is based on the well-established MET principle. The different activity values have been validated by combining them to a typical week day of an ISS astronaut and calculating the daily kilocalorie demand. The result is very similar to values presented by NASA[21].

The physical-chemical technologies are based on chemical process formulas which are assumed to be accurate.

The model has flows at certain spots which do not connect to another model part but rather end in a sink or start from a source outside the model border. This is the case, for example, for the O_2 consumption and CO_2 production by the crew inside the gases layer module. It is therefore important to check the model closure with respect to the fundamental elements carbon, oxygen and hydrogen which make up all the material in the model. A closed model would not lose or gain any carbon, oxygen or hydrogen throughout the whole simulation. A few additional model building blocks have been added to the model to perform the necessary calculations.

In principle one has to sum up all the carbon, oxygen and hydrogen contained in the whole system and calculate the sums every time step to see whether they change or not. For compounds of multiple elements such as carbon dioxide, water and food the respective molecular ratios of the elements need to be taken into account for the calculations.

Table 3 shows the results of the model closure validation simulation. In general one can see that the model generates additional elements during the calculations. Carbon and hydrogen are almost in balance with only small surpluses between the values at mission start and mission end. Oxygen shows a higher surplus at mission end compared to the other two elements. Since the other two elements are almost in balance the larger surplus of oxygen might be related to a minor imbalance in the calculation of the respiratory quotient of the crew. This could result in a minor imbalance between consumed oxygen and produced carbon dioxide by the crew. The calculation of the respiratory quotient however looks plausible and no error could be identified.

In general the model has a high degree of closure with a small daily deviation of 0.0282 kg/d (carbon, oxygen and hydrogen combined). When comparing this deviation to the total amount of carbon, oxygen and hydrogen contained in the model stocks, the model gains 2.379×10^{-4} % of its original total mass per day. The deviations are fairly constant throughout the whole simulation duration and consequently add up over time. The total model closure calculated after 500 simulation days is 99.881 %. This value is good enough for the simulations envisioned for this model.

Table 3: Results of the model closure validation.

	Carbon (C)	**Oxygen (O)**	**Hydrogen (H)**
Amount at the start of the simulation [kg]	2574.323	8450.524	812.180
Amount at the end of the simulation [kg]	2574.352	8464.552	812.183
Difference [kg]	+0.029	+14.038	+0.003
Difference [%]	$+1.127 \times 10^{-3}$	$+1.662 \times 10^{-1}$	$+3.694 \times 10^{-4}$
Deviation [kg/d]	$+5.80 \times 10^{-5}$	$+2.81 \times 10^{-2}$	$+6.00 \times 10^{-6}$

V. Mars Surface Habitat Simulation Scenario

A. Description

The model setup for this simulation scenario represents a Mars surface habitat architecture. The mission architecture and therefore the simulation inputs are partially based on NASA's Human Exploration of Mars Design Reference Architecture 5.0[22]. The simulation scenario incorporates a Mars surface habitat with a hybrid life support system consisting of physical-chemical life support technologies as well as a greenhouse for plant cultivation. Figure 2 shows the life support architecture in the conventional way, indicating mass flows between the different subsystems, the crew and the plants.

The simulation inputs defined for this simulation scenario are explained in detail in a separate publication by Zabel[13].

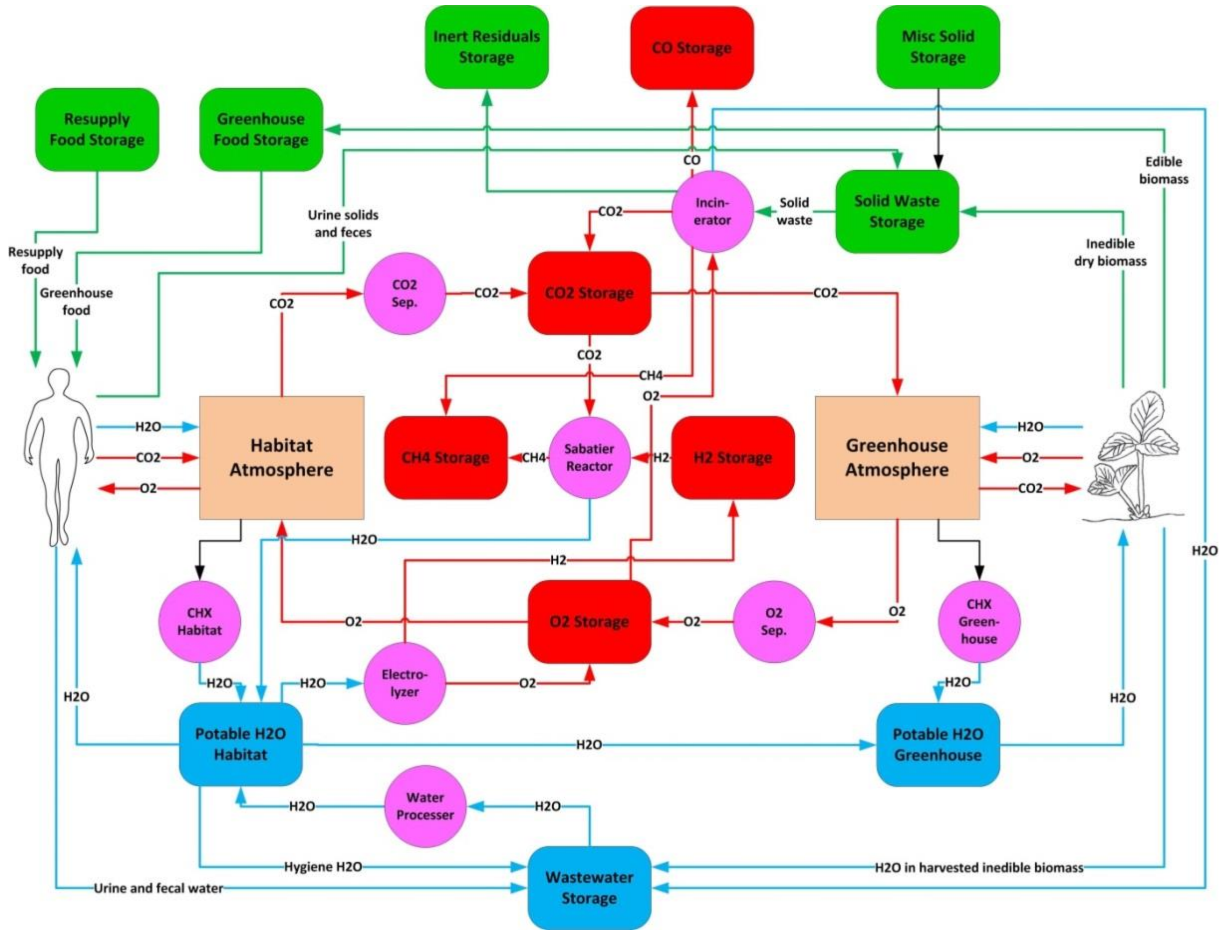


Figure 2: Life support system architecture for the Mars surface habitat simulation scenario. Physical-chemical systems are in purple, liquid mass flows in blue, gaseous mass flows in red and solid mass flows in green.

B. Simulation Results for Nominal Operation

1. Overview

For the simulation of the Mars surface habitat scenario, the model was run with the simulation inputs to simulate the nominal operation of the life support system. Nominal operation in this case means:

- All crew members survived the mission in good shape.
- The stocks for potable water, oxygen, carbon dioxide and food stayed within ranges to sustain all crew members.
- No system failures or other perturbations have been included.

2. Oxygen and carbon dioxide

The oxygen concentration in the atmosphere of the habitat and the greenhouse is constant at 21 % of the pressurized volume. This behavior is caused by the strict control of the oxygen flows, which are implemented in the model to assure crew survival. The concentration of carbon dioxide inside the greenhouse, see Figure 3, also has a strict control to assure that the concentration does not fluctuate too much in order to provide a controlled environment for the plants. The concentration of carbon dioxide in the greenhouse atmosphere is constant at the desired value of 1000 ppm throughout the whole simulation. There is a step on mission day 1 in the graph for the greenhouse carbon dioxide, which is caused by the initial fill up from the carbon dioxide storage stock.

While the concentration inside the greenhouse is strictly controlled, the carbon dioxide in the habitat can fluctuate. Normally the greenhouse takes up the carbon dioxide produced by the crew inside the habitat to keep the concentration inside the habitat at the nominal level of 4000 ppm. In case the greenhouse cannot take up all the carbon dioxide produced, the physical-chemical systems take over the carbon dioxide reduction once the upper threshold of 7000 ppm is reached. This behavior can be seen in Figure 3. At the start and at the end of the mission when the greenhouse is not at full capacity the carbon dioxide in the habitat rises to the upper threshold and is kept at this level by the physical-chemical systems.

There are however two more spikes in the habitat carbon dioxide concentration, one around day 180 and one around day 267. These spikes indicate a low carbon dioxide uptake capability of the greenhouse. The crop production schedule causes this behavior. The spikes are in line with the harvest of the soybean compartment which has the largest cultivation area and therefore the largest carbon dioxide uptake. At the second spike between day 256 and day 279, six out of nine active compartments are harvested in a span of two and a half weeks. Only the compartments with the peanut, sweet potato and tomato plants still have plants and the tomato and sweet potato plants are only one and a half weeks old and not yet at full carbon dioxide uptake capability. The described behavior is the evidence of the influence of the production schedule on the balance of the life support mass flows.

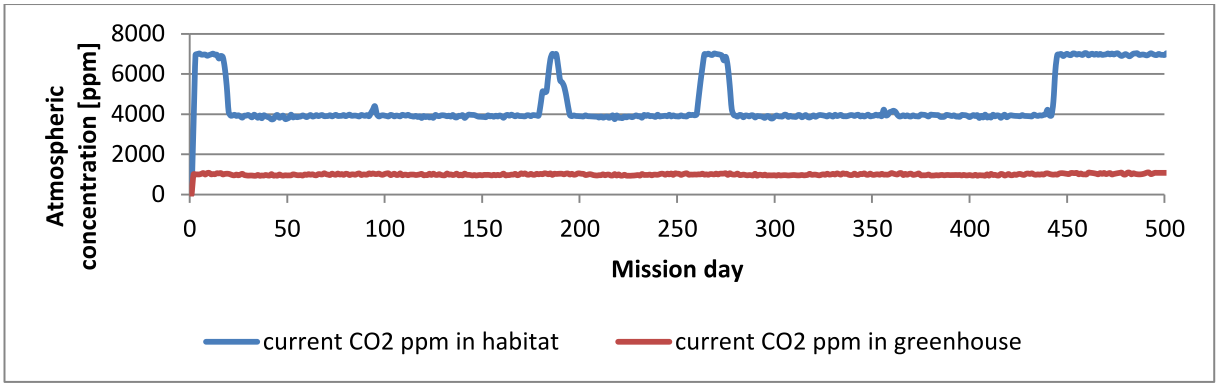


Figure 3: Atmospheric concentration of carbon dioxide inside the habitat and the greenhouse under nominal operation.

The spikes in concentration of carbon dioxide inside the habitat atmosphere are caused by an imbalance between production by the crew and consumption by the greenhouse. The rates of production and consumption of carbon dioxide are shown in Figure 4. Whenever the carbon dioxide in the habitat raises above the nominal level the consumption of carbon dioxide by the greenhouse is lower than the production by the crew.

While the crops' consumption of carbon dioxide varies depending on the production cycle, the production from the crew members is fairly constant. The cycles in the production graph of the crew in Figure 4 is caused by the weekly cycle of the crew activity (five days normal activity followed by two days with reduced activity).

A graph for the oxygen production respectively consumption is not shown here, because there is a direct dependency to the carbon dioxide consumption respectively production.

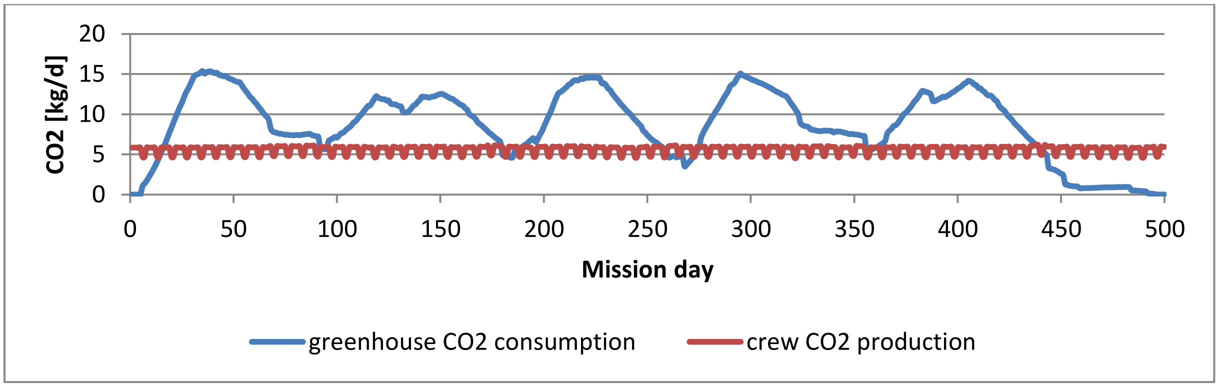


Figure 4: Greenhouse carbon dioxide consumption and crew carbon dioxide production under nominal operation.

The other two stocks involved in the oxygen and carbon dioxide loops besides the habitat and the greenhouse are the storage stocks. The behavior of these for the simulation under nominal operation is shown in Figure 5. The oxygen storage stock has a steep decline on mission day 1 caused by the initial fill up of the habitat and greenhouse atmosphere.

During the first 23 days the amount of carbon dioxide in the storage stock slightly rises and the amount of oxygen decreases slightly. From day 23 until day 81 the behavior changes in the opposite direction. The amount of oxygen rises and the amount of stored carbon dioxide falls slightly. This behavior is caused by the growth rates of the plants and therefore by their carbon dioxide uptake and oxygen production. At the beginning the capacity of the greenhouse to contribute to the life support system is small but rises fast until the first harvest of compartments with a large amount of plants around day 81. Due to these harvests events there is a large amount of inedible biomass stored and there is also excess oxygen in the oxygen storage. Those are conditions under which the incinerator and the inedible biomass processor start to recycle the solid waste products. Consequently, the carbon dioxide storage is constantly at its upper threshold, because consumed carbon dioxide is replenished immediately by the two systems. Since the carbon dioxide storage is at the upper threshold, excess oxygen accumulates over time in the oxygen storage.

The last phase of the mission from day 450 onwards is characterized by the declining greenhouse capacity. The excess carbon dioxide produced by the crewmembers and their demand in oxygen is now exchanged with the storage stocks. The oxygen storage stock declines and the carbon dioxide storage stock rises.

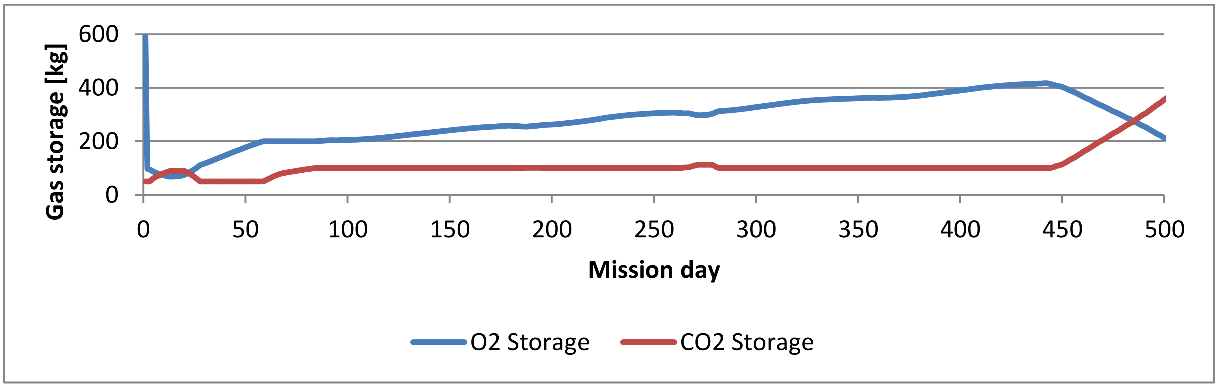


Figure 5: Amount of oxygen respectively carbon dioxide in the storage stocks under nominal operation.

3. Carbon monoxide, methane and hydrogen

The last components of the gases layer module to be discussed are the storage stocks for carbon monoxide, methane and hydrogen. The behavior of the three stocks is shown in Figure 6. As mentioned before, around day 40 the incinerator starts the recycling of solid waste products. Since the incinerator produces carbon monoxide and methane as by-products, the amount of gas stored in the storage stocks slowly rises. Note that all the methane is produced by the incinerator, because the Sabatier reactor is not active throughout the whole simulation. The same is true for the electrolyzer which also not active and therefore the hydrogen storage stock remains zero all the time.

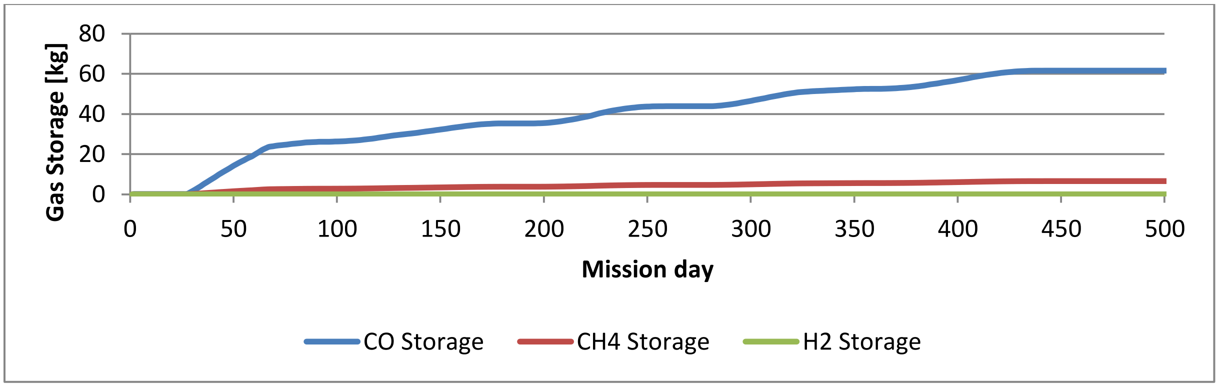


Figure 6: Amount of carbon monoxide, methane and hydrogen gas in their respective storage stocks under nominal operation.

4. Potable water, wastewater and water in living plants

The liquids layer module calculates all water stocks and flows of the life support system. Of particular importance are the potable water storage in the habitat, the potable water storage in the greenhouse, the wastewater storage and the water accumulated in the living plant biomass. Their behavior during the simulation is shown in Figure 7. The graphs for the water contained in the body of the crew members, the habitat atmosphere and the greenhouse atmosphere are not shown here, because these stocks are kept constant by strict control parameter throughout the whole mission.

The potable water storage in habitat stock has a step on day 1, because the stock is used to initially fill up the habitat atmosphere with humidity and the potable water storage in greenhouse stock, see Figure 7. Between day 1 and day 14 is a slight increase in potable water in the habitat caused by the water recovery from the habitat atmosphere and the crew wastewater recycling. From day 14 until day 67 a steep decrease of the amount of water in the habitat potable water storage can be observed. This is caused by the potable water demand from the greenhouse potable water storage which is in turn caused by the water accumulating in the growing amount of living plant biomass. Consequently, there is a transfer from the potable water storage in the habitat to the living plant biomass.

The water accumulating in the living plant biomass is transferred upon harvest to the wastewater storage stock. The downward step in accumulated water at day 67 and day 81 indicate harvest events of a large amount of plants. The wastewater is recovered by the VPCAR and directed back into the potable water storage of the habitat.

Figure 7 also provides evidence of the long-term water cycles in the life support system of the simulated Mars surface habitat. There is a constant cycle of water coming from the potable water storage in the habitat, going to the potable water storage in the greenhouse and from there into the living plant biomass and from there into the wastewater storage upon harvest and back into the potable water storage of the habitat after recycling.

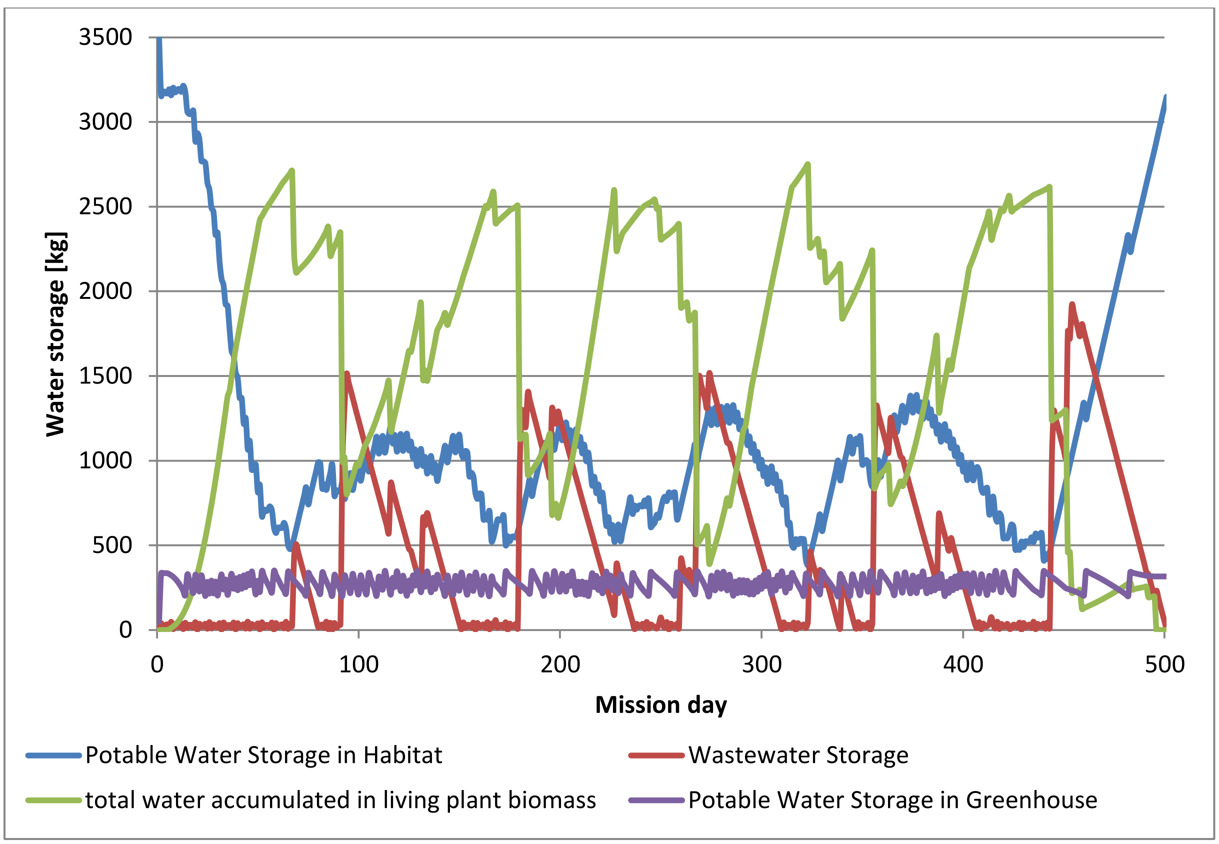


Figure 7: Behavior of the four main water stocks in the Liquids Layer module under nominal operation.

The wastewater recycling by the VPCAR plays an important role in the life support system's water cycle. The VPCAR recycles wastewater coming from four different sources: the water accumulated in the inedible biomass, the water produced by the incinerator, the water produced by the inedible biomass processor and the wastewater produced by the crew. In total the VPCAR has to recycle roughly 35000 kilograms of wastewater throughout the mission. Figure 8 shows the ratio of the four wastewater sources. The crew wastewater and the water accumulated in the inedible biomass make up around 98% of the wastewater production.

While the production of wastewater by harvesting and drying inedible biomass is also evident in Figure 7, the crew wastewater production cannot be observed directly in these graphs. This is caused by the difference in total production of the crew and the recycling capacity of the VPCAR. The wastewater production by the crew members is fairly constant at 40 kg/d throughout the mission. Since the VPCAR capacity of 75 kg/d is significantly higher than the crew wastewater production, the effect of the latter on the wastewater storage cannot be seen in Figure 7.

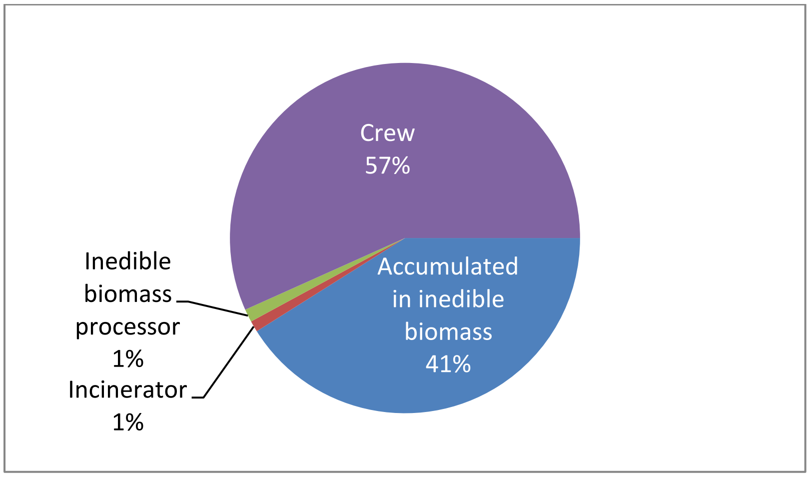


Figure 8: Ratio of the total wastewater production over the whole simulation duration under nominal operation.

5. Biomass

The solids layer module calculates the values for the plant biomass inside the greenhouse, the two food storage stocks (resupply and greenhouse food) and the two solid waste stocks for crew waste and harvested inedible biomass. The previous two chapters already mentioned the influence of the greenhouse production schedule on certain mass flows of the life support system. The graphs shown in Figure 9 can explain most of the observed behavior. The figure shows the accumulated curves of the dry biomass contained in the living plants.

Since the oxygen production and carbon dioxide consumption of the crops is correlated to their size, which means their biomass, the greenhouse potable water graph shown in Figure 7 follows the cycle of the crop biomass shown in Figure 9.

There is a long-term oscillation with a period of around 97 days in Figure 9. This oscillation is caused by compartment five which contains the soybean plants. Since soybean makes up most of the greenhouse diet and therefore requires the largest cultivation area, the growth cycle of this compartment has the strongest impact on the dry biomass in living plants graph. The soybean oscillation is then overlapped by the growth cycles of the other crops, which causes the smaller spikes in the dry biomass graph.

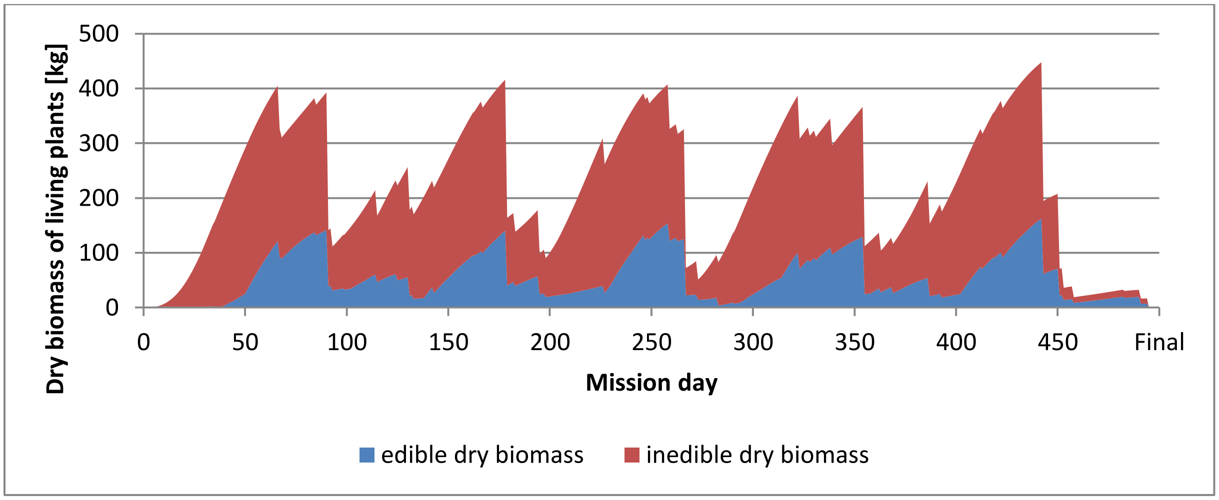


Figure 9: Dry biomass accumulated in living plants inside the greenhouse under nominal operation.

6. Food

The food consumed by the crew is a mix of resupply food brought from Earth and the food grown in the greenhouse, as mentioned in previous chapters. Figure 10 shows the consumption rates of resupply food and greenhouse of the whole crew. The small oscillations observed in the resupply food curve are caused by the weekly cycle of the crew activity (five days of normal activity followed by two days of reduced activity). At the start of the mission the crew relies solely on the resupply food until the first crops are harvested around day 40, day 65 and day 95. From day 95 onwards the greenhouse produces constantly enough food to contribute more to the overall food consumption than the resupply food. There are however four interruptions in the greenhouse food consumption graph. Those are most likely caused by depleting the food stock of a certain crop before the next harvest event. The resupply food storage is able to compensate for the missing greenhouse food.

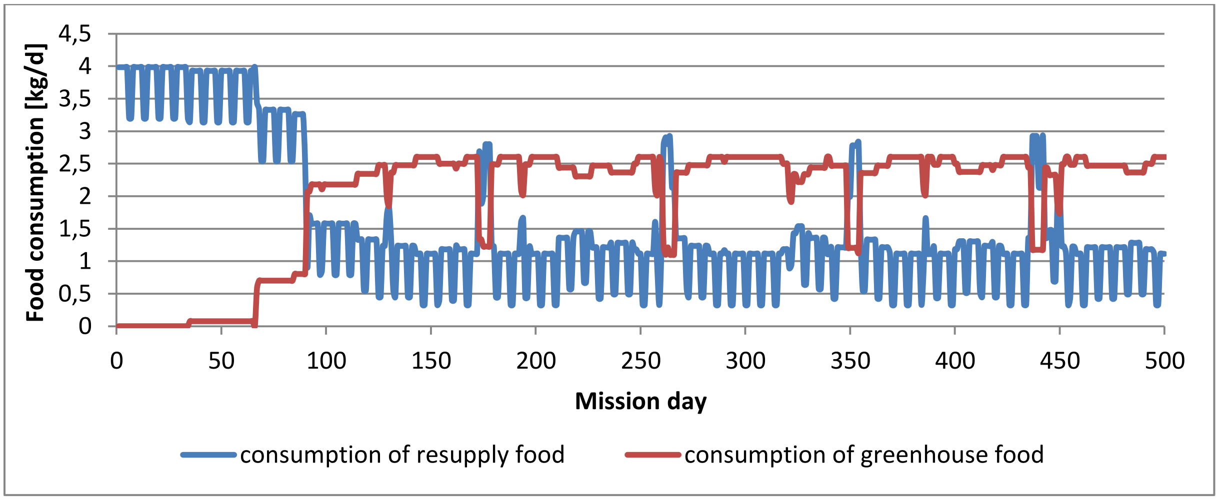


Figure 10: Crew food consumption from resupply storage or greenhouse food storage under nominal operation.

Figure 11 shows the amount of food present in the resupply storage and the greenhouse storage stocks over the mission duration. The resupply food storage steadily declines, because it is only initially filled at mission start and because there is no scheduled resupply mission in this simulation scenario. The resupply food storage however declines more in the early days of the mission when the crop food starts to provide most of the food. From there one the resupply food storage stock depletes slower. The crop food storage oscillates in correlation to the greenhouse production schedule.

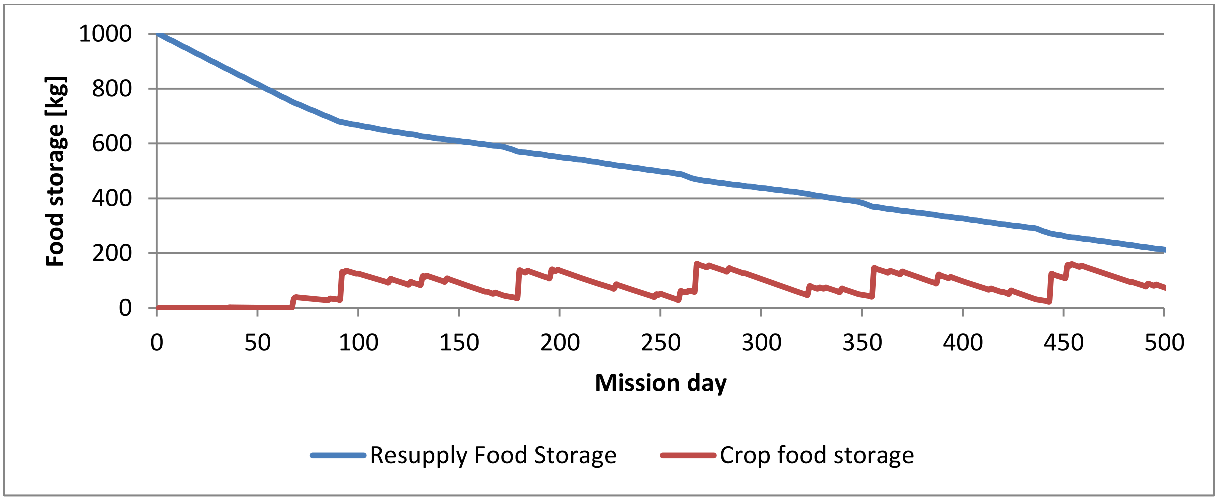


Figure 11: Amount food in the resupply storage and the crop food storage under nominal operation.

7. Solid waste

The crew and the greenhouse produce a large amount of solid waste products over the course of the mission. The graphs for the corresponding storage stocks are shown in Figure 12. The solid waste storage in habitat stock value constantly increases due to the waste production by the crew of roughly 12.5 kg/d. The incinerator is in theory capable of processing the produced waste products. The carbon dioxide storage at the upper threshold however prevents the system from recycling more waste. The harvested inedible dry biomass also increases over time out of the same reason.

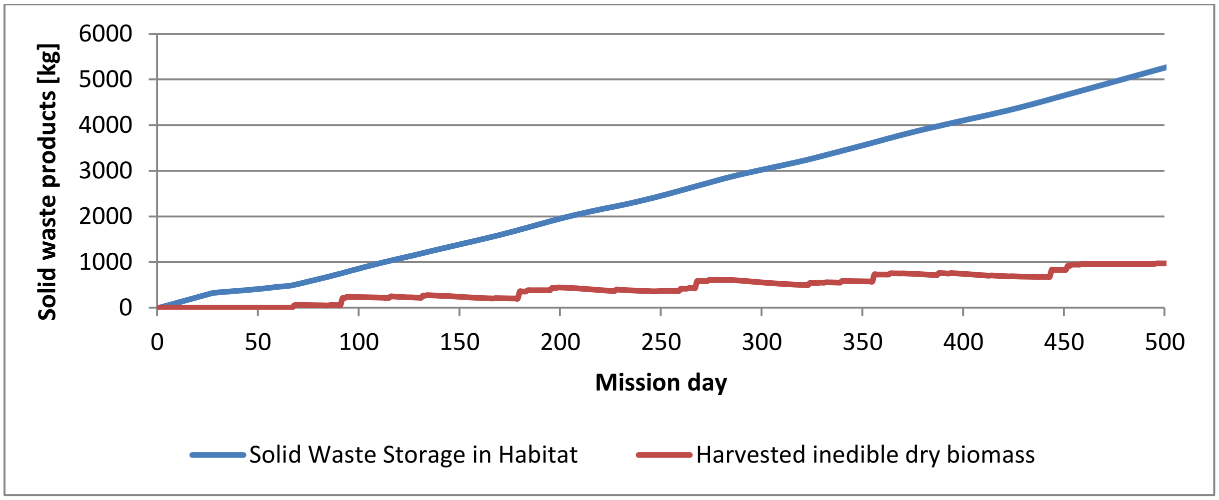


Figure 12: Behavior of the solid waste storage and the harvested inedible dry biomass storage under nominal operation.

8. Physical-chemical systems

The physical-chemical systems implemented in the model take over major roles in the life support system architecture. These systems are however not constantly active, but their activity is controlled by different parameters. The importance of the VPCAR water recycling system is evident from Figure 13. The VPCAR is active on 453 out of the 500 mission days in order to transform wastewater into potable water for the crew and the plants.

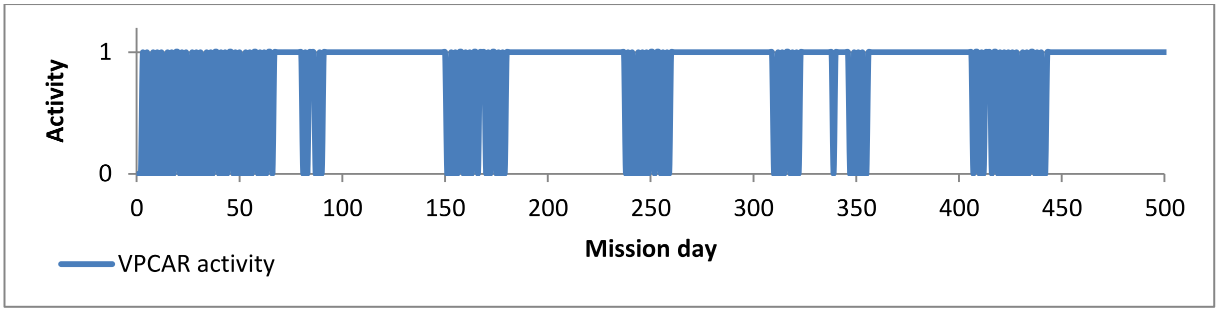


Figure 13: VPCAR activity under nominal operation (active=1; inactive=0).

The activity of the incinerator and the inedible biomass processor is restricted by the carbon dioxide storage upper threshold. Figure 14 and Figure 15 prove that fact. While there are still enough solid waste products to be processed (see Figure 12), both systems are only working in short intervals and are only active on roughly 110 days throughout the mission.

The electrolyzer and the Sabatier reactor are implemented as backup systems in the model. That is done by having the thresholds for the systems activation at thresholds which should not be reached under nominal operation. Consequently, the both systems are not active during this simulation scenario.

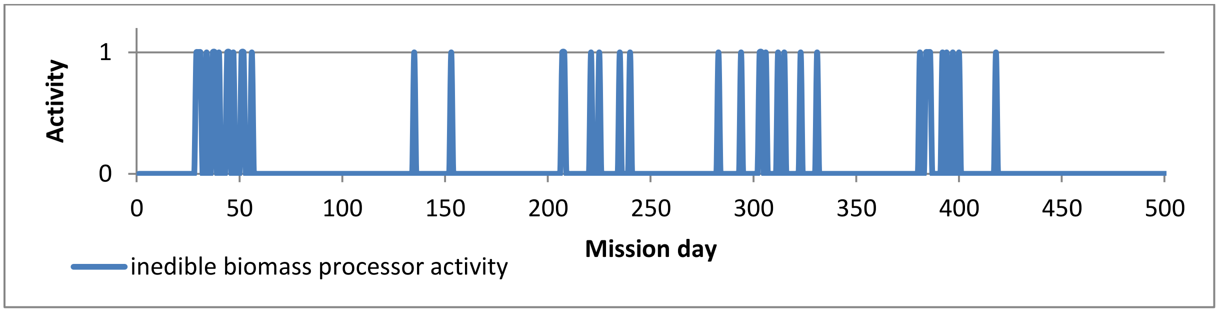


Figure 14: Inedible biomass processor activity under nominal operation (active=1; inactive=0).

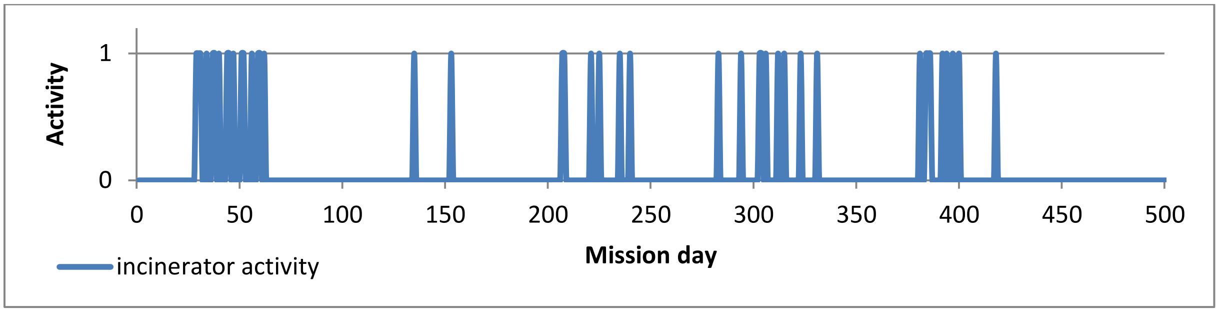


Figure 15: Incinerator activity under nominal operation (active=1; inactive=0).

VI. Discussion

A. Model

The described model allows the investigator to setup a wide range of input parameters such as mission duration, habitat size, crew size and composition, greenhouse production schedule etc. for a hybrid life support system. Implementing the input parameters can be partially done via predefined excel tables and partially by modifying the code of the model.

The model has been setup utilizing the SD approach, which uses only a few building blocks and a graphical programming language. This makes it easier for new users to understand and use the model. By using the Stella Professional software for the programming of the model the user is provided by a wide range of investigation options such as built-in sensitivity and perturbation analysis tools. Simulation results can be easily exported as excel files.

The developed model consists of a habitat model (represented by a gases layer, a liquids layer and a solids layer), a crew model, a greenhouse model and models for different physical-chemical technologies. The three layers of the habitat model act as backbone of the over model. The layers manage the exchange of matter and information between the other components of the model and calculate the related mass flows.

The crew model is a responsive input and output model. The crew can be defined by the number of crew members and their gender, age and weight. A crew scheduler allows the user of the model to schedule different activities for each crew member to specific crew member days and these days to a mission profile. The crew model then calculates the different crew member inputs and outputs based on the activity level of each day. There are more sophisticated human models (which model the human metabolism in detail) available for space life support system simulations than the one developed for this model. In order to reduce simulation times and complexity of the model, only an input and output model was established.

The greenhouse model is based on the MEC crop model. The cultivation of nine different crop species can be simulated and their inputs and outputs calculated. The calculations are sensitive to a range of environmental conditions. The greenhouse model has a crop scheduler which allows the user of the model to setup a specific greenhouse production schedule (e.g. seeding, harvest dates, growth cycles). The model can simulate a greenhouse of up to ten different compartments with different environmental settings (e.g. light intensity, carbon dioxide concentration).

Since the greenhouse model utilizes the MEC plant model it also inherits its weaknesses. The MEC plant model can only be used to simulate plant development for a very specific range of environmental conditions. Outside these boundaries the simulation results are not validated against experimental data. Furthermore there are only formulas for nine plant species mainly high caloric density plants (e.g. wheat, potato, beans). A real space greenhouse would most likely be used to cultivate a more diverse set of plants, but those cannot be simulated with the model. The original MEC model lacked formulas for water accumulation in plant tissue and metabolic water consumption during photosynthesis. These formulas have been added to improve the model.

The different implemented physical-chemical technology models are based on formulas of chemical processes. This procedure is convenient for achieving mass closure of the overall model, but it comes with the downside that process efficiencies are not yet implemented in the model.

B. Simulation

A 500 day Mars surface mission with a crew of six was simulated to demonstrate the functionality of all model parts. The mission scenario is based on NASA's Mars Design Reference Architecture 5.0 (DRA 5.0). The life support system architecture utilizes a space greenhouse for food production and an array of physical-chemical technologies for air, water and waste treatment. The whole mission was simulated under nominal conditions, which in this case means no internal or external perturbations whatsoever.

The behavior of the life support system is strongly affected by the production schedule of the greenhouse. During the first 100 days of the mission, for example, the greenhouse acts as a large resource sink taking up and binding almost all of the potable water in the system and also a lot of carbon and oxygen. All these elements are used to build up the plant biomass and the water in the plant tissue. From day 100 on the overall behavior of the system is defined by the production cycle of the largest plant compartment (in this case soybean), which leads to a cyclic behavior with a period of around 90 days. This behavior could be compensated by the physical-chemical technologies and the implemented buffers.

The simulation shows the importance of a reliable water recycling system (e.g. VPCAR) in order to guarantee that there are no water shortages throughout the mission. The condensing heat exchanger systems are of similar importance especially to recover the large amount of water transpired every day by the plants in the greenhouse. There is surplus oxygen accumulating over the course of the mission, because the resupply food and misc solid equipment consumed are subsequently transformed first into mostly carbon dioxide (by the waste recycling system) which is than transformed by the plants into oxygen. Dry solid waste and dry inedible biomass is also accumulating throughout the mission, because there was no need for additional carbon dioxide. The initial amount of resupply food is 1000 kg. Of this amount, 350 kg are not consumed under nominal operational conditions and act as buffer for contingencies.

The startup phase of the greenhouse is a critical period of the whole mission. The startup of the greenhouse results in large mass redistributions within the life support system. The greenhouse acts as a resource sink for the first roughly 90-100 days with the used simulation settings. After that period the simulated hybrid life support system has a cyclic behavior. This behavior is caused by the implemented crop production schedule. Always when the capability of the greenhouse to consume carbon dioxide and produce oxygen is limited due to the production schedule, the survival of the crew is at risk. A perturbation e.g. a system failure during that period could lead to a lethal mission end.

The simulation results show a minimum in available potable water of 29 kilograms on day 229. This amount of water is less than the tolerable minimum for a crew of six with an average potable water demand of around 48 kg/d (includes around 31 kg/d hygiene water) and a greenhouse full of plants. The minimum in potable water is not caused by a general lack of available water. There are 870 kilograms of unprocessed wastewater stored inside the wastewater storage. The control parameters and the capacity of the VPCAR water recycling system seem to be of high importance for the modelled system architecture to avoid shortages in potable water.

Over the whole mission the life support system has accumulated around 5200 kg of solid waste and around 920 kg of unprocessed harvested inedible biomass. The incinerator and the inedible biomass processor are not able to recycle more solid material, because of the thresholds set on the CO_2 and O_2 storage stocks.

It is also evident from this simulation that the end of the mission when the greenhouse performance declines might be critical situation if system failures happen during that period.

VII. Summary

The development of a new ECLSS model to simulate hybrid life support systems is described in this paper. The model is capable of simulating a wide range of mission scenarios and system settings which allows the user exploratory analysis of future hybrid life support system architectures. The simulation of a 500 day Mars surface habitat mission illustrates the functionality of the model for nominal mission characteristics without internal or external perturbations. This simulation already revealed a number of critical situations of the modelled ECLSS architecture during the mission. These critical situations and other perturbations and sensitivity analyses are the strengths of the developed model. Simulations investigating a wide range of possible perturbations (e.g. greenhouse startup phase, crop failure, subsystem failures) and sensitivity analyses (e.g. VPCAR capacity, CHX capacity, crop performance) are already ongoing using the model described in this paper.

Appendix

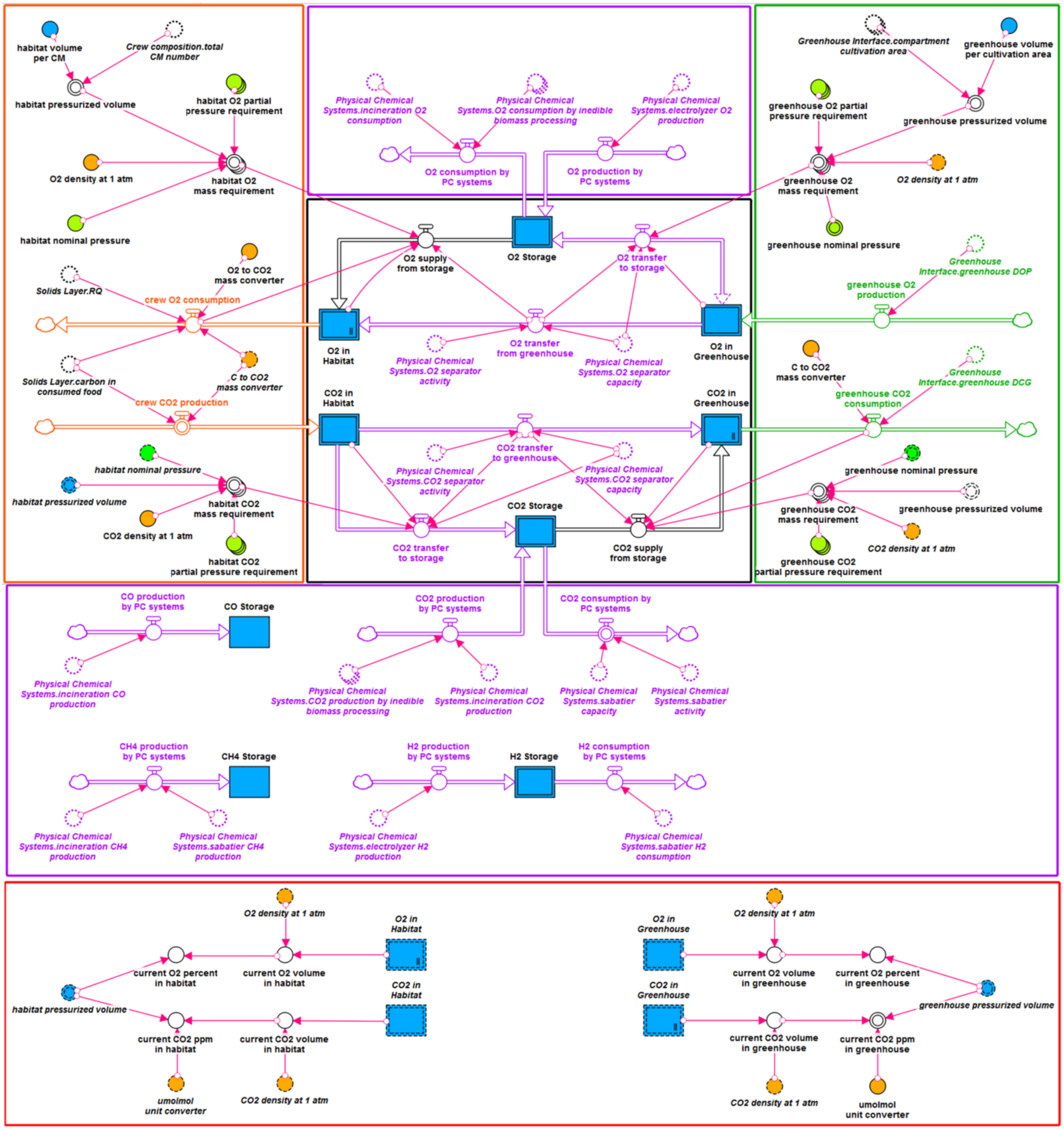


Figure 16: Overview of the gases layer module. Frames indicate different parts of the module. Black frame: Core; Orange frame: Crew; Green frame: Greenhouse; Purple frames: Physical-chemical systems; Red frame: Atmospheric composition conversions.

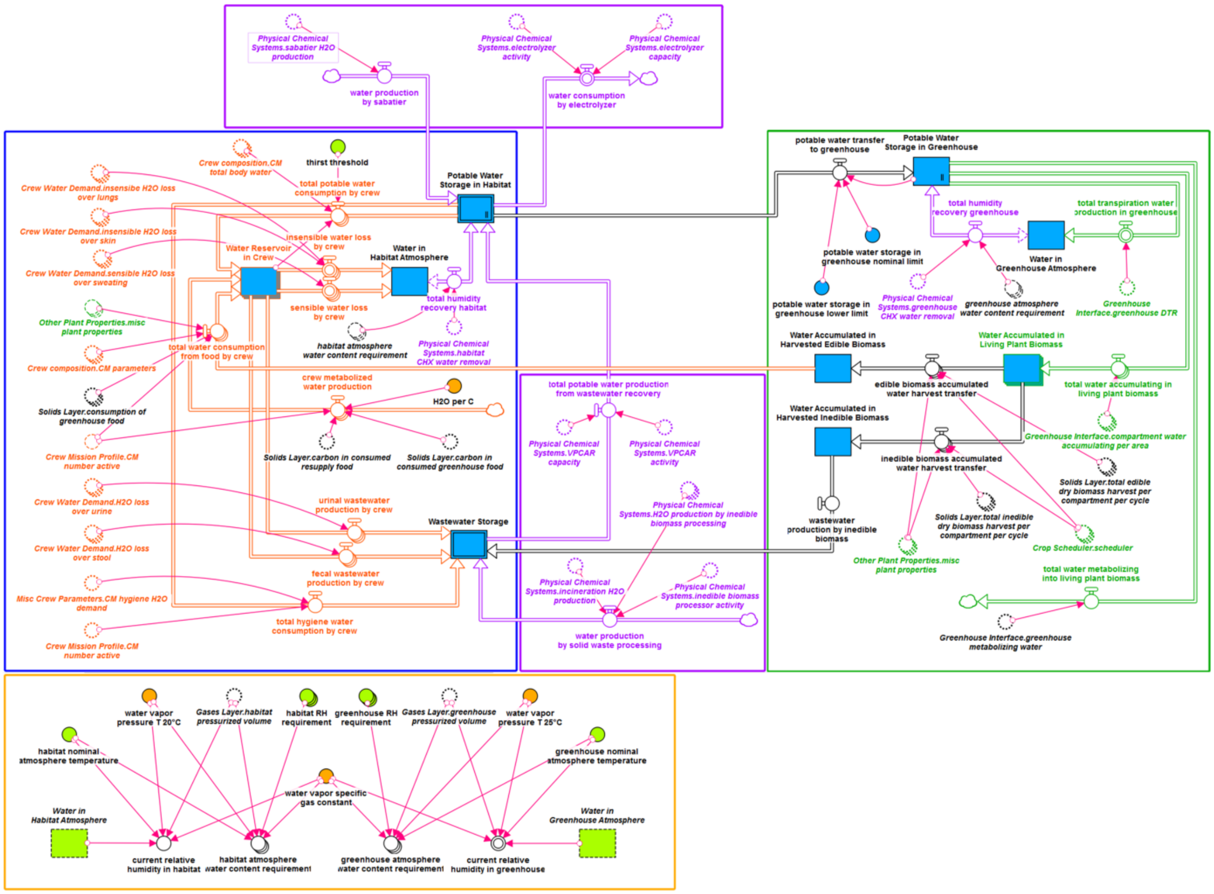


Figure 17: Overview of the liquids layer module. Frames indicate different parts of the module. Blue frame: Crew; Green frame: Greenhouse; Purple frames: Physical-chemical systems; Orange frame: Humidity conversion.

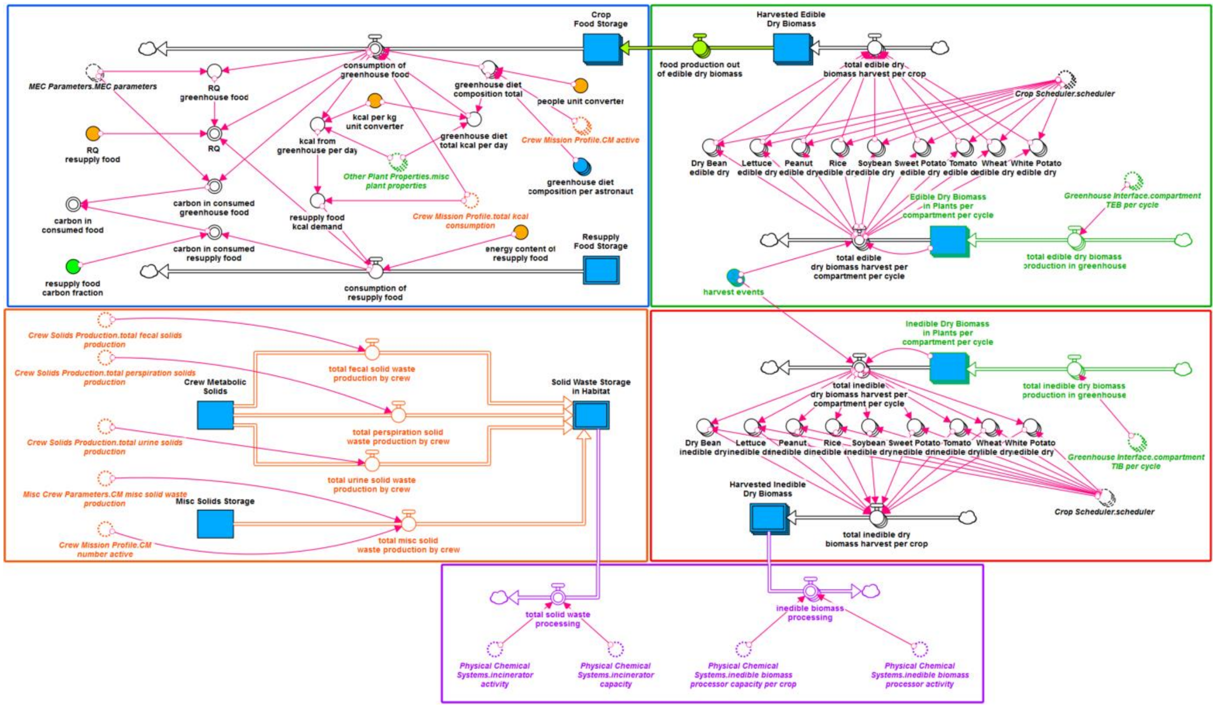


Figure 18: Overview of the Solids Layer module. Frames indicate different parts of the module. Blue frame: Crew food; Orange frame: Crew waste; Green frame: Edible biomass harvest; Red frame: Inedible biomass harvest; Purple frame: Physical-chemical systems.

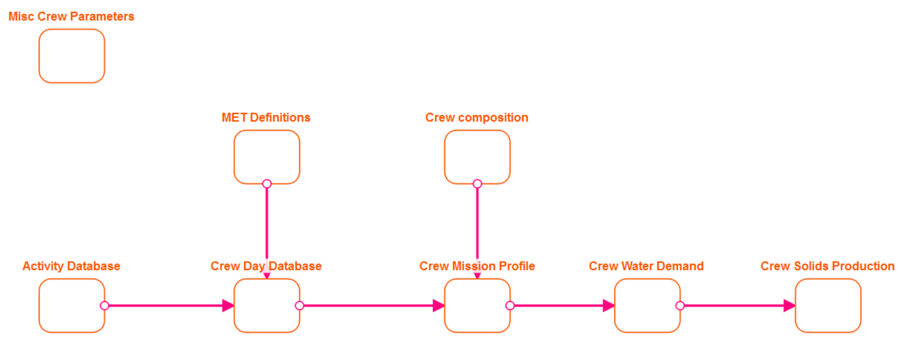


Figure 19: Crew model module.

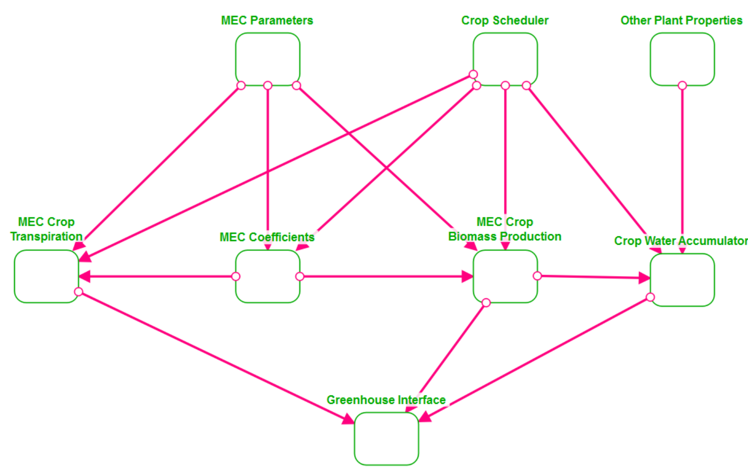


Figure 20: Greenhouse model module interconnections in Stella.

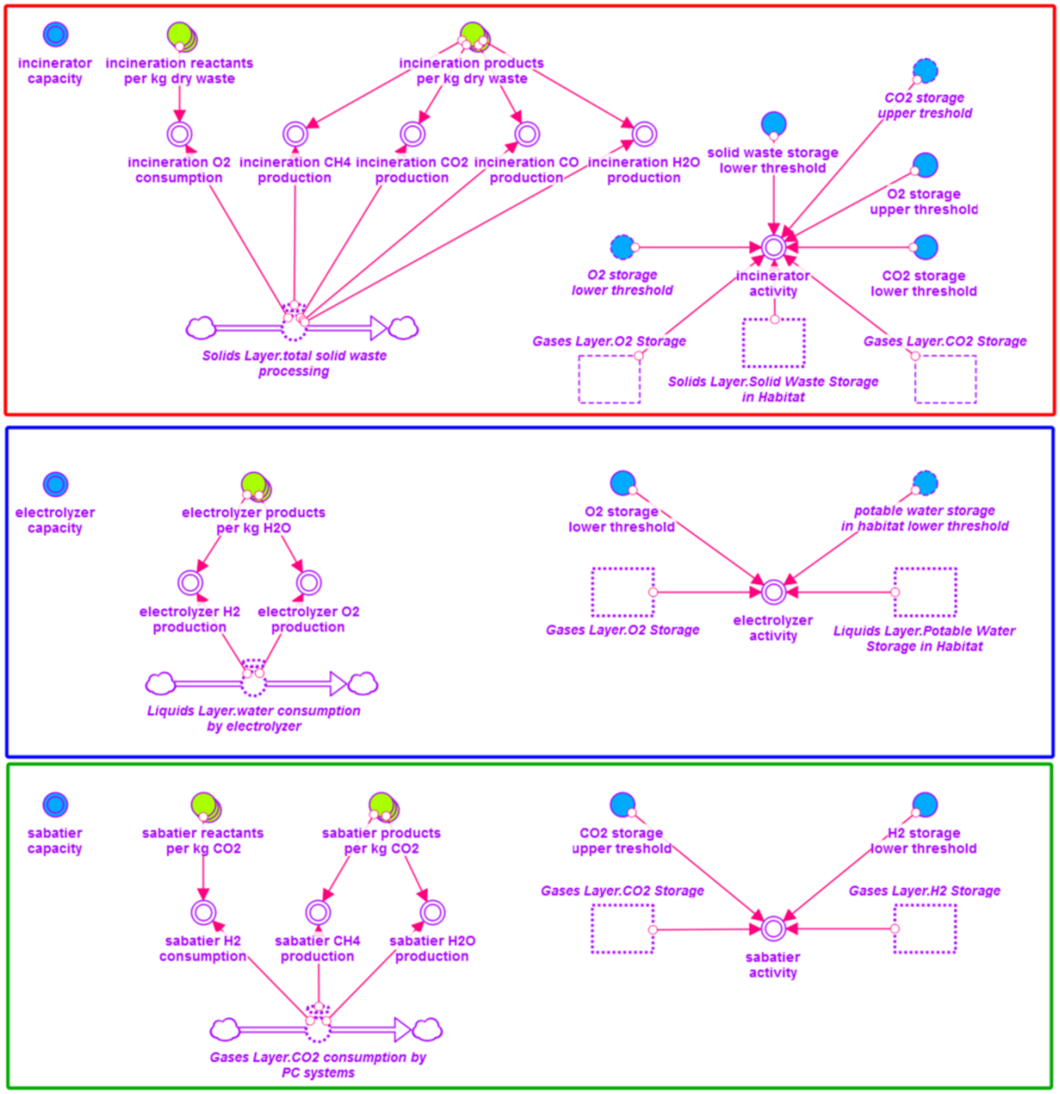


Figure 21: Overview of the top part of the physical-chemical systems module. Red frame: Incinerator calculations, blue frame: Electrolyzer calculations, green frame: Sabatier Reactor calculations.

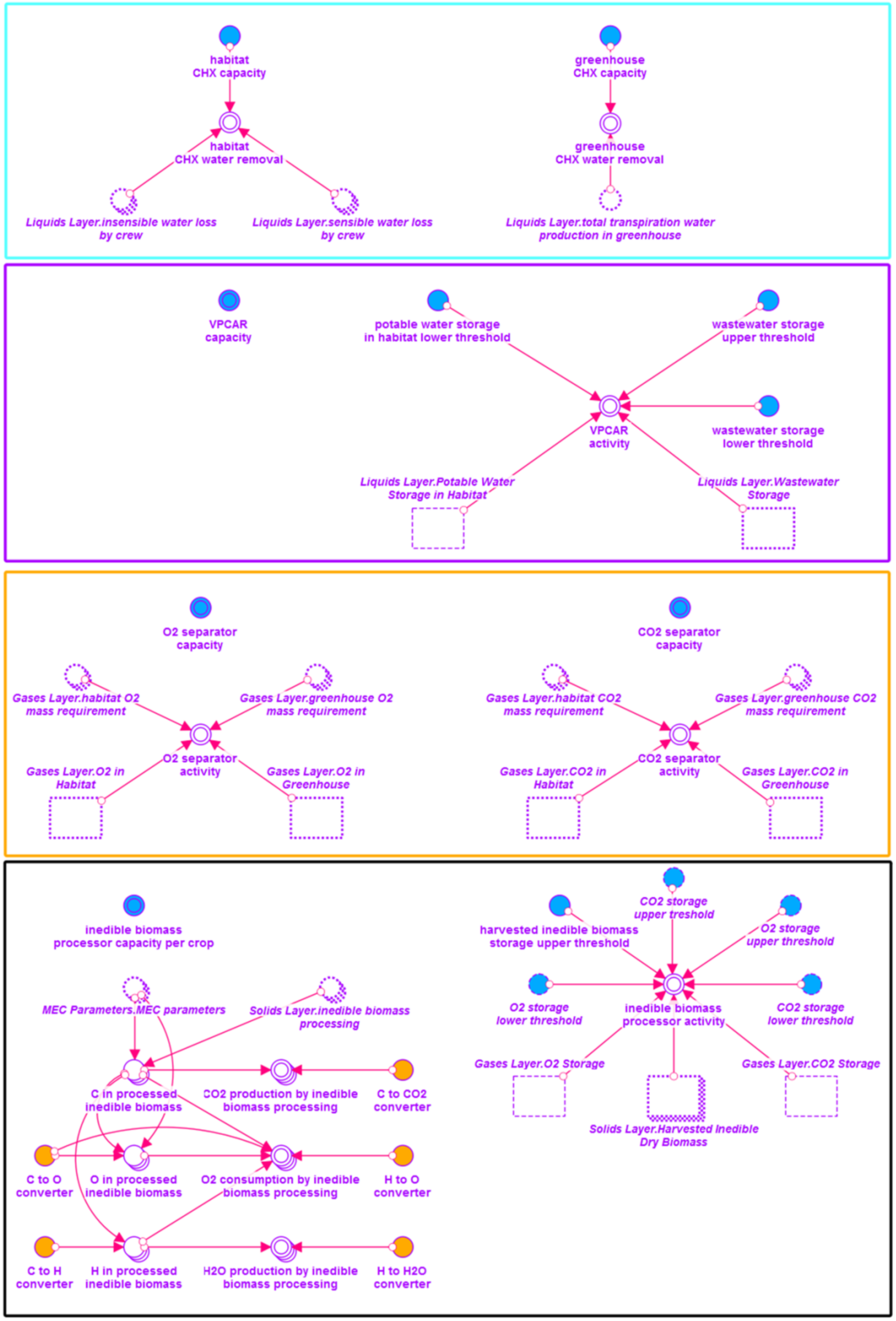


Figure 22: Overview of the bottom part of the physical-chemical systems module. Teal frame: CHX calculations, purple frame: VPCAR calculations, yellow frame: Oxygen and carbon dioxide separator calculations, black frame: Inedible biomass processor.

Acknowledgments

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References

[1]Jones, H. W., "How Should Life Support be Modeled and Simulated?," *47th International Conference on Environmental Systems,* Charleston, South Carolina, 2017.

[2]Meadows, D. H., and Wright, D., *Thinking in systems. A primer,* Chelsea Green Pub., White River Junction, Vt, 2008.

[3]Ford, A., *Modeling the environment,* 2nd ed., Island Press, Washington, DC, 2010.

[4]Coyle, R. G., *Management system dynamics,* Wiley, London, New York, 1977.

[5]Forrester, J. W., *Industrial dynamics,* Pegasus Communications, Waltham, MA, 1961.

[6]Forrester, J. W., *Urban dynamics,* Pegasus Communications, Waltham, Mass, 1969.

[7]Meadows, D. H., *The Limits to growth;. A report for the Club of Rome's project on the predicament of mankind,* Universe Books, New York, 1972.

[8]Ruth, M., and Hannon, B. M., *Modeling dynamic economic systems,* 2nd ed., Springer, New York, 2012.

[9]Robinson, W. A., *Modeling Dynamic Climate Systems,* Springer New York, New York, NY, 2001.

[10]Deaton, M. L., and Winebrake, J. J., *Dynamic Modeling of Environmental Systems,* Springer New York, New York, NY, 1999.

[11]Hannon, B. M., and Ruth, M., *Modeling dynamic biological systems,* Springer, New York, 1997.

[12]Hargrove, J. L., *Dynamic modeling in the health sciences,* Springer, New York, 1998.

[13]Zabel, P., "An investigation of the dynamic behavior of a hybrid life support system and an experiment on plant cultivation with a urine-derived nutrient solution," PhD Dissertation, Technical University Dresden, Institute for Aerospace Engineering, Dresden, 2019.

[14]Jetté, M., Sidney, K., and Blümchen, G., "Metabolic equivalents (METS) in exercise testing, exercise prescription, and evaluation of functional capacity," *Clinical Cardiology*, Vol. 13, No. 8, 1990, pp. 555–565.

[15]McArdle, W. D., Katch, F. I., and Katch, V. L., *Exercise physiology. Nutrition, energy, and human performance*, 2014.

[16]Cavazzoni, J., "Using explanatory crop models to develop simple tools for Advanced Life Support system studies," *Advances in Space Research*, Vol. 34, No. 7, 2004, pp. 1528–1538.

[17]Jones, H., and Cavazzoni, J., "Top-Level Crop Models for Advanced Life Support Analysis," *30th International Conference on Environmental Systems,* Toulouse, France, 2000.

[18]Jones, H., Cavazzoni, J., and Keas, P., "Crop Models for Varying Environmental Conditions," *32nd International Conference on Environmental Systems,* San Antonio, Texas, 2002.

[19]Volk, T., Bugbee, B., and Wheeler, R., "An approach to crop modeling with the energy cascade," *Life Support and Biosphere Science*, Vol. 1, 1995, pp. 119–127.

[20]Jones, H., Cavazzoni, J., and Keas, P., "Crop Models for Varying Environmental Conditions," *32nd International Conference on Environmental Systems,* San Antonio, Texas, 2002.

[21]Anderson, M. S., Ewert, M. K., Keener, J. F., and Wagner, S. A., "Life Support Baseline Values and Assumptions Document," *NASA,* NASA/TP-2015–218570, 2015.

[22]Drake, B. G., *Human Exploration of Mars Design Reference Architecture 5.0,* NASA, 2009.