MELiSSA system studies

Full Loop Model Integration and What-if Scenario Simulations

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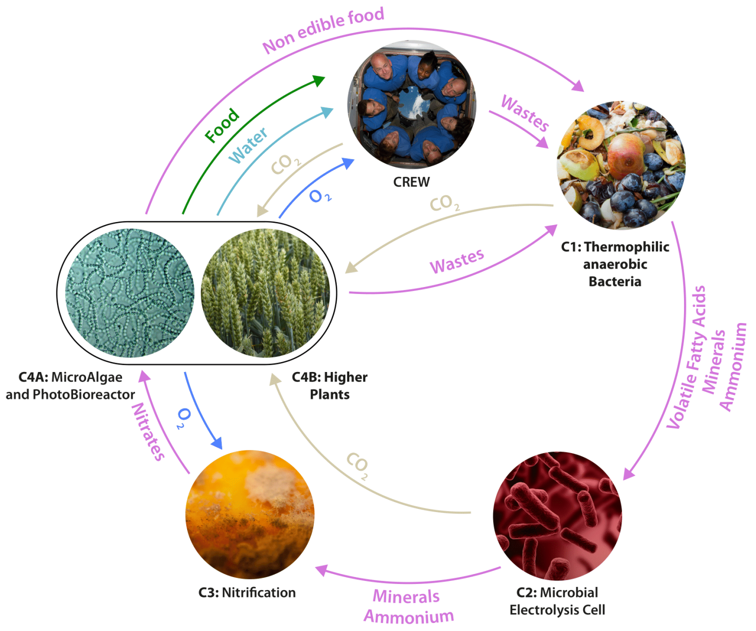
Project VARSITY

VARSITY
VARiuS Integration of system sTudY for model-based cybernetics for the control of complex systems

OBJECTIVES

- Upgrade formulation of mathematical mechanistic models to have a homogeneous formulation for all compartments
- Simulate the full MELiSSA loop, and coordinate the five compartments simultaneously
- Provide ESA & Space Industries with an evaluation tool for Life Support Systems

This activity has been performed in the frame of the MELiSSA Memorandum of Understanding (ESA 4000100293) and funded by the European Space Agency's Exploration Preparation Research and Technology (ExPeRT) programme, within the Terrae Novae European Exploration Envelope Programme (E3P).



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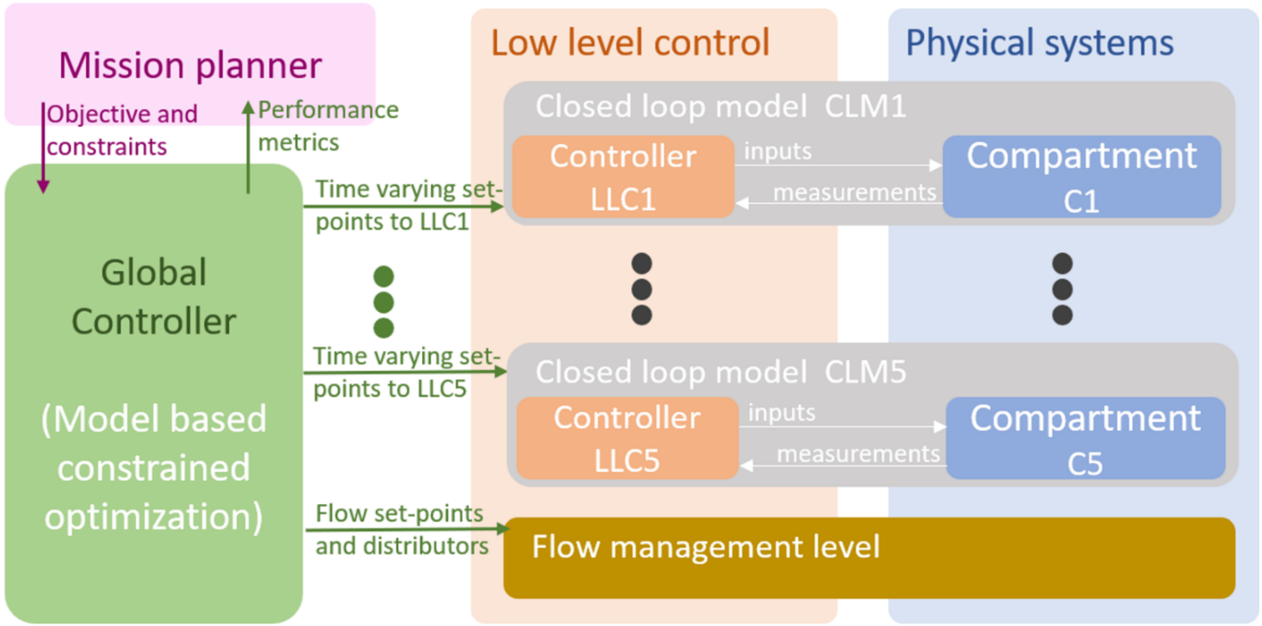
Control Structure for a Regenerative LSS

Hierarchical control structure on 3 levels

- **Low-level control**: real-time control of compartments (local goals)
- **Global controller**: real-time coordination of the network (supervisor)
- **Mission planner**: decision maker in a space mission timeframe



This work focuses on the Global Controller

1. elaboration and formalization of the control strategy
2. implementation of a Model Predictive Control (MPC)
3. test on selected scenarios (including fault scenarios)

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Why MPC for an LSS supervisor?

MPC: state-of-the-art for advanced process control

Explicit use of the network **mathematical model** for prediction:

- Can effectively handle complex systems, different timescales, and coupled dynamics
- Easy to upgrade compartments' models, and network architecture
- Reconfiguration in real-time, to face system failures or operating modes

Formulation as a constrained optimal control problem:

- Easy to include multiple (and conflicting) objectives (survival, efficiency, recirculation)
- Many requirements are formulated in terms of ranges
- Possibility to exploit the predictability of some aspects (crew schedule, day/night)
- Easy to interface with the mission planner (modify cost and constraints)

The objective is to build an enabler for consolidating the structure

MPC Formulation for the Global Controller

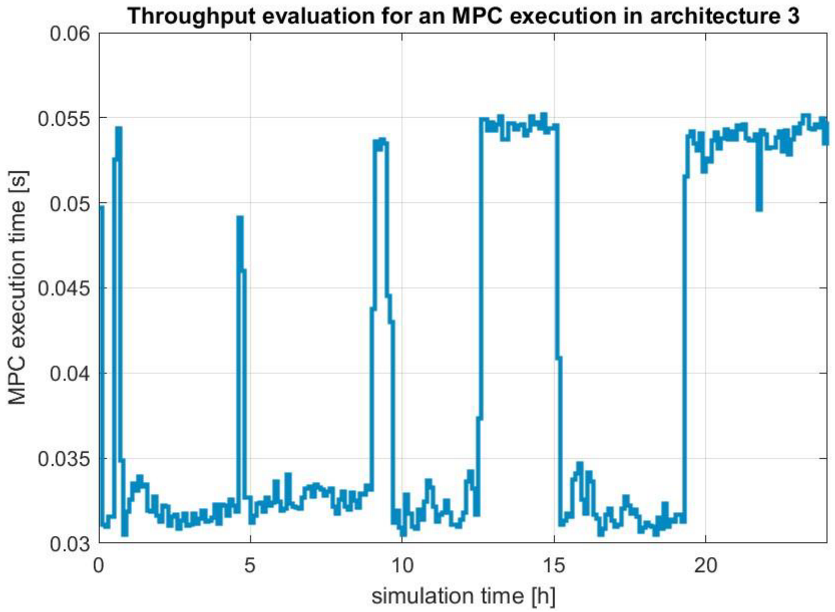
Optimize (recycling & recovery + use of extra resources + control effort)

subject to: nonlinear model dynamics
actuators bounds
storage constraints
safety & survivability constraints

sampling time: 6 minutes
prediction horizon: 1 hour

Non-linear time-varying MPC with:

- **270** optimization variables
- **2270** dynamics equalities (system dynamical model)
- **760** inequality constraints
- prediction model with **227** states, **26** inputs, **14** outputs



"ODYS Embedded MPC" software library for MPC solutions in real-time applications

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Mathematical model of the network

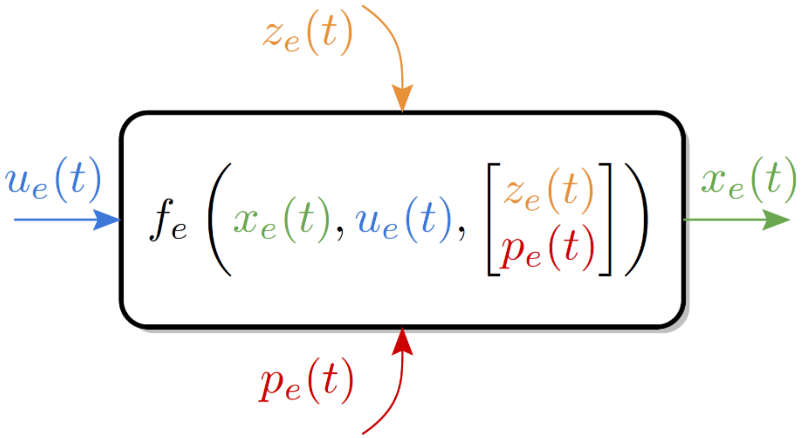
Generic formulation for the mathematical model of the LSS:

- **dynamics** of the compartments and compartments' interactions
- focus is on **modularity**
    - seen as composition of submodules
    - **33 chemical elements** in solid, liquid and gas phases

$$\frac{\mathrm{d}x(t)}{\mathrm{d}t} = f(x(t), u(t), p(t))$$
$$y(t) = h(x(t))$$

Compartments modelled with stoichiometric equations and first order dynamics

submodel parameters: function of loop states and inputs (ex. output states from another compartment)



submodel inputs: variables manipulated by the controller

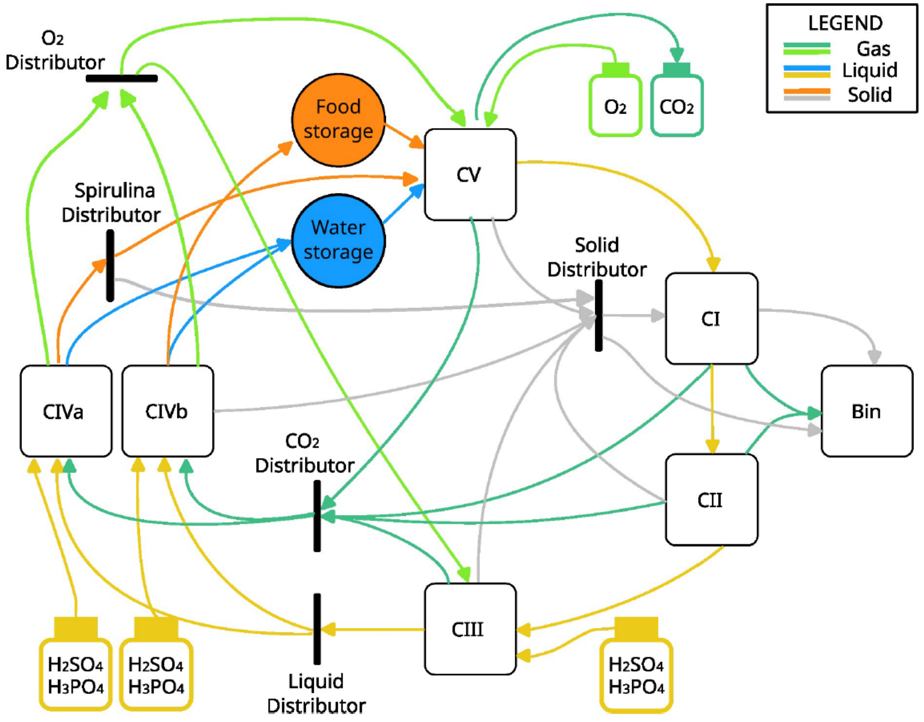
submodel states: flows and volumes

global parameters: time-varying parameters (ex. crew diet)

Control Inputs and Time-Varying Parameters

Control inputs (directly manipulated by the global controller):

- **distributors** (5): route flows from multiple sources
- **manipulated flows** (C4a, C5): control the output flows of components'
- **buffer tanks** (up to 18): supplements of chemical components
    - in the architecture's selection, **the number of tanks is minimized**
- **activities** (C4a, C4b): modulate the production rate of a compartment



Time-varying parameters:

- **crew needs** (9): food mass, diet, water and O2 needs
- **plant needs** (1): CO2 needs of the plants

$$\mathrm{diet}(t) = \begin{bmatrix} \{\text{proteins}\}(t) \\ \{\text{lipids}\}(t) \\ \{\text{carbs}\}(t) \\ \{\text{nucleic}\}(t) \\ \{\text{eps}\}(t) \\ \{\text{fibres}\}(t) \end{bmatrix}$$

Parameters can vary according to some schedule (day/night cycle, crops, etc.), or for unforeseen events

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Tests Setup and Evaluation

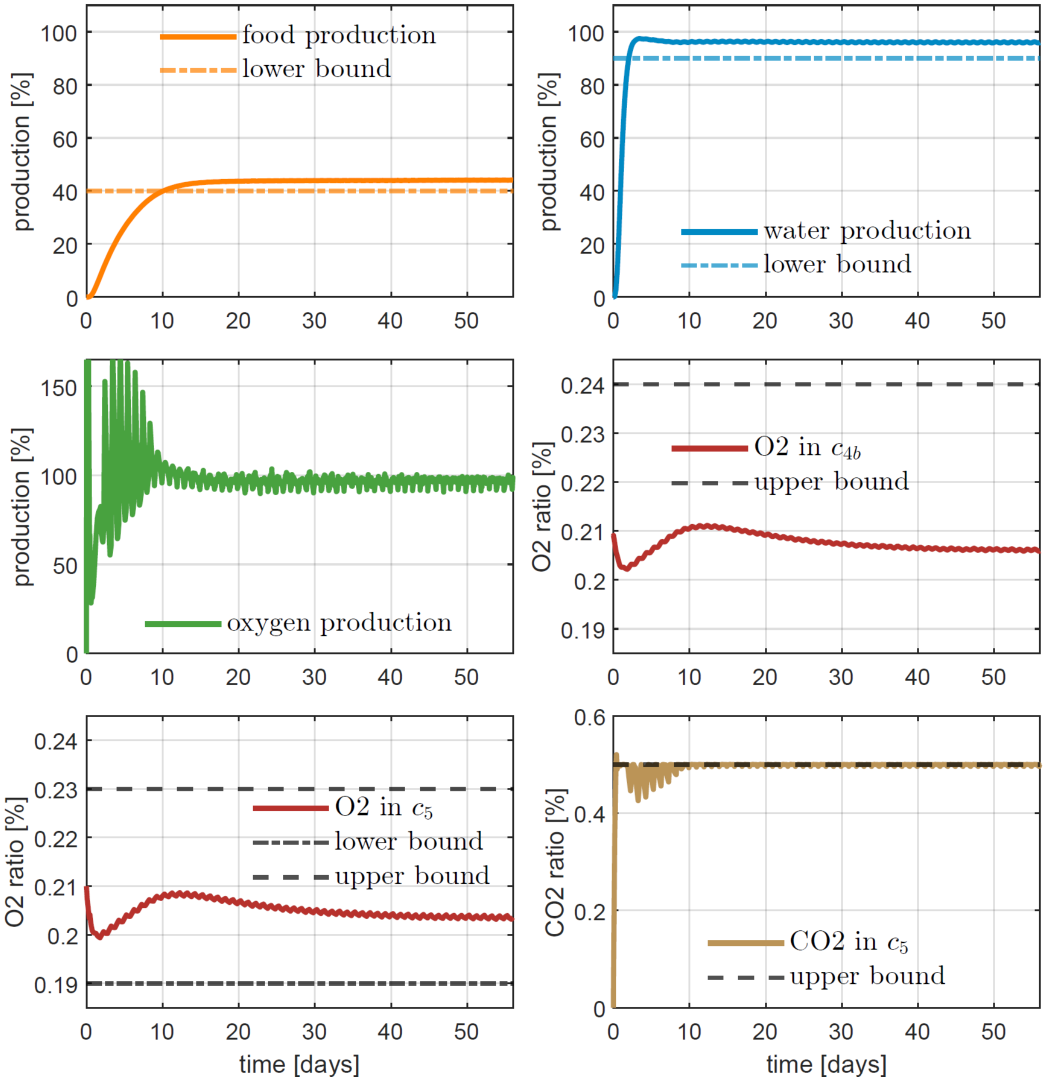
- evaluation of **10 architectures**
  - different buffer storages
- investigation of **variable crew needs**
  - oxygen needs
- **sensitivity** studies:
  - cabin and the greenhouse volumes
  - change in the cultivated crops
- **4 what-if scenarios**:
  - crew is sick
  - C3 failure
  - C4a efficiency drop
  - change in crew needs

	O2	CO2	HNO3	H2SO4	H3PO4	NH3	H2SO4	H3PO 4	VFA, NH3
	C5	C4a,b	C4a,b	C4a,b	C4a,b	C3	C3	C3	C2
Arch. 1	X								
Arch. 2	X				X			X	
Arch. 3	X			X	X		X	X	
Arch. 4		X	X	X	X				
Arch. 5		X	X	X	X		X	X	
Arch. 6			X	X	X		X	X	X
Arch. 7	X					X	X	X	
Arch. 8	X			X	X	X	X	X	
Arch. 9	X	X		X	X	X	X	X	
Arch. 10	X			X	X	X	X	X	X

One single MPC correctly handles all the architectures and test scenarios

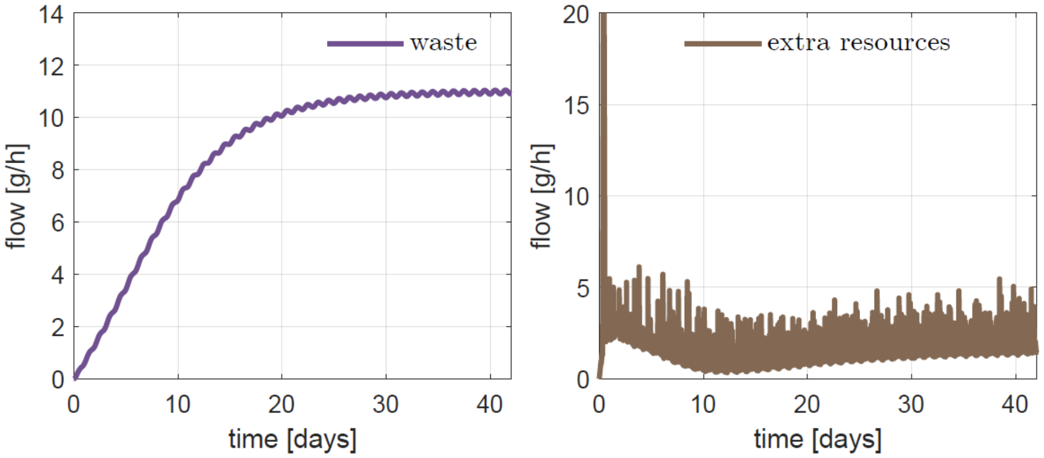
ALISSE criteria have been evaluated for all tests

Detailed Results for One Configuration



The system under the supervisor control satisfies all the requirements in all the scenarios

Component	Phase	Waste (kg)
C1 biomass	S	0.6992
Undegraded organic matter	S	10.2333
Dihydrogen	G	1.4178



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Achievements and Future Directions

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ACHIEVEMENTS:

- **Methodology** for the global control of a circular life support system
- First implementation of an **advanced supervisory controller** for a complete circular life support system
- Preliminary **dynamical simulation of MELiSSA loop** architectures considering all the compartments connected in all the phases

VARSITY – PHASE 2

FUTURE DIRECTIONS:

- Equip the compartments with **mechanistic models and a low-level controller**
- **Expand the set of requirements** (e.g. energy consumption and survival for plants and microalgae)
- Improve the **cost function definition** (impact of specific type of waste and additional resources)
- Consider a **hierarchical MPC** formulation, possibly organized according to the chemical phases

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Thank you!

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