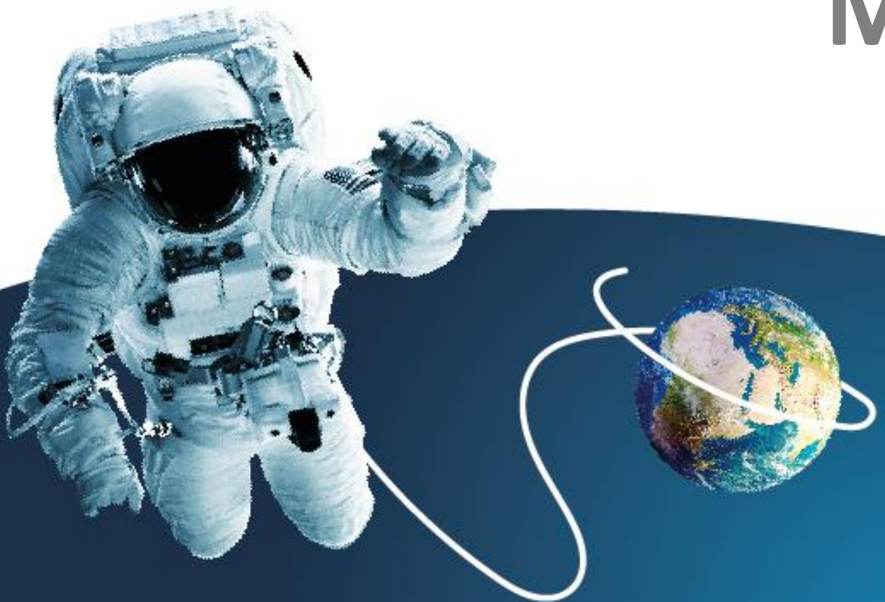
MELiSSA
MICRO-ECOLOGICAL LIFE SUPPORT SYSTEM ALTERNATIVE

CREATING A CIRCULAR FUTURE

Model structuration and review for MELiSSA knowledge and control.



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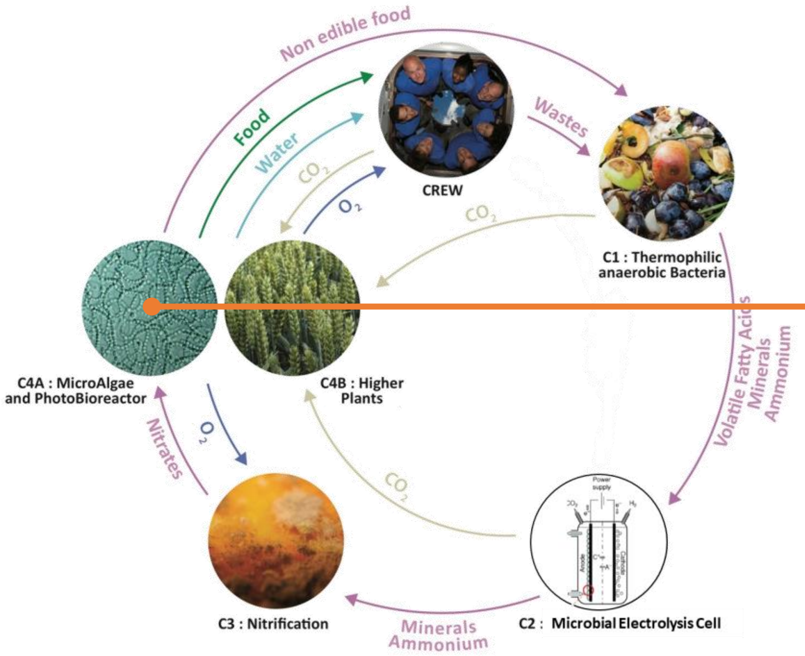
MELiSSA (Micro-Ecological Life Support System Alternative)

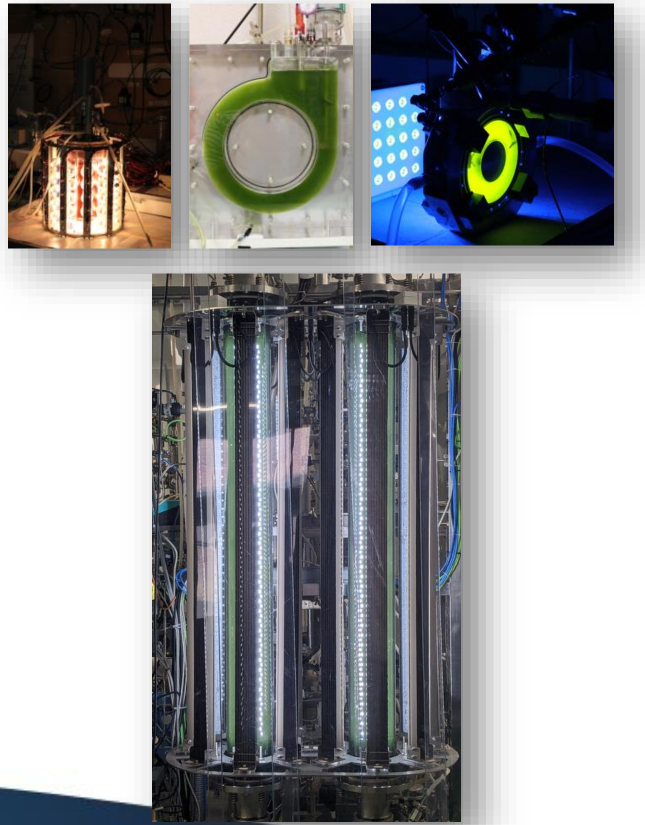
- concept inspired from a lacuste (lake) ecosystem
- gain knowledge on regenerative systems, aiming to the highest degree of autonomy and consequently to produce food, water and oxygen from mission wastes

Engineered approach : split the complex system into « unit operations/functions » (=compartments) which are investigated separatly (but within the objective of the complete loop integration)

** Credit : UAB-MELiSSA Pilot Plant 2007*

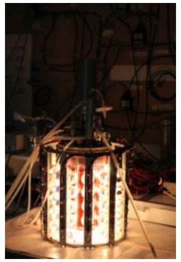


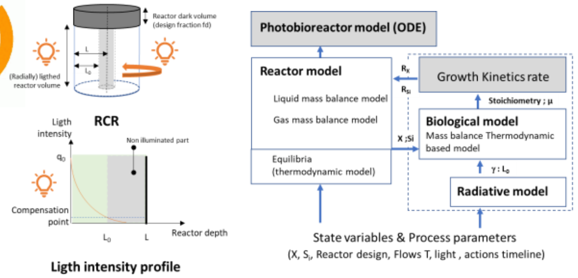
C4a : photobioreactor – Oxygen + food



Compartments studies, models & modelling objectives

experimental **(to gain) knowledge & mechanistic model**





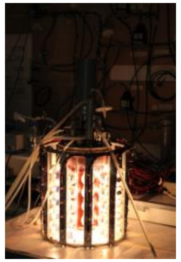
Knowledge model: enables the representation of knowledge and the division of a process in subparts that can be studied individually, as well as their interactions.

Mechanistic model: it is based on physical, chemical, and biological laws describing the elemental mechanisms and processes of the system of interest. Mechanistic models are classified among the knowledge models.

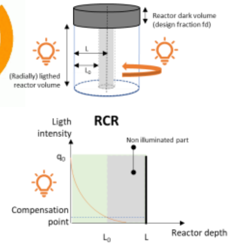
Deterministic model: for a given input, the model output is always the same creating a form of determinism between inputs and outputs of system. The determinism is generally supported by mathematical expressions and results of calculations. The results are obtained either by solving systems of equations or by averaging stochastic calculations (e.g., Monte Carlo simulations). In the last case, the determinism includes the determination of the average values and of their standard deviations.

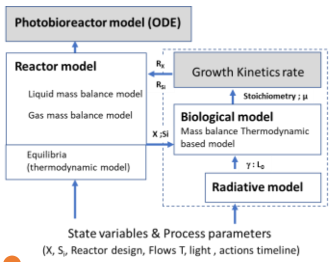
Compartments studies, models & modelling objectives

experimental



(to gain) knowledge & mechanistic model





Understanding (gain knowledge)

Mastery of the process

- Characterization (mass-energy balances)
- optimisation/operation
- control
- sizing

Rebuit the loop with models of compartements

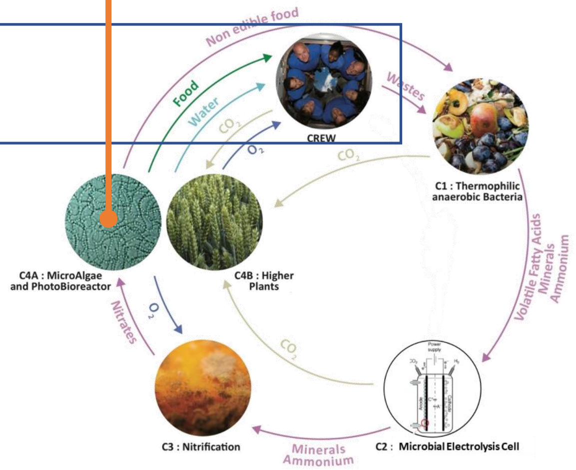
LSS functions

1 – atmosphere

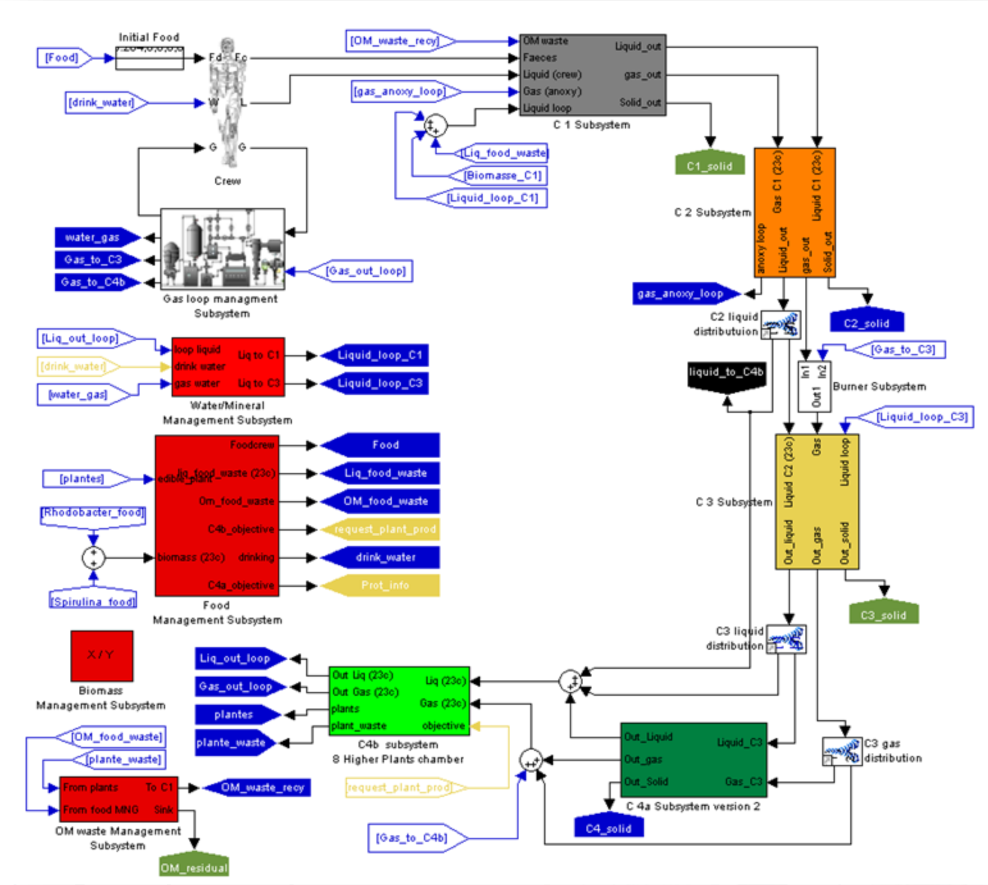
2 – water

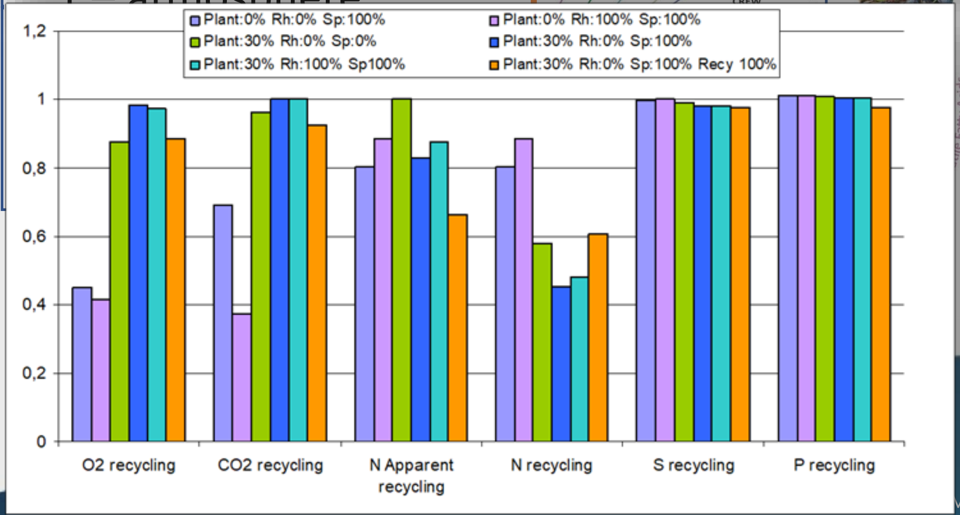
3 – wastes

4 - food



studies, models & modelling objectives/usage





Understanding (gain knowledge)

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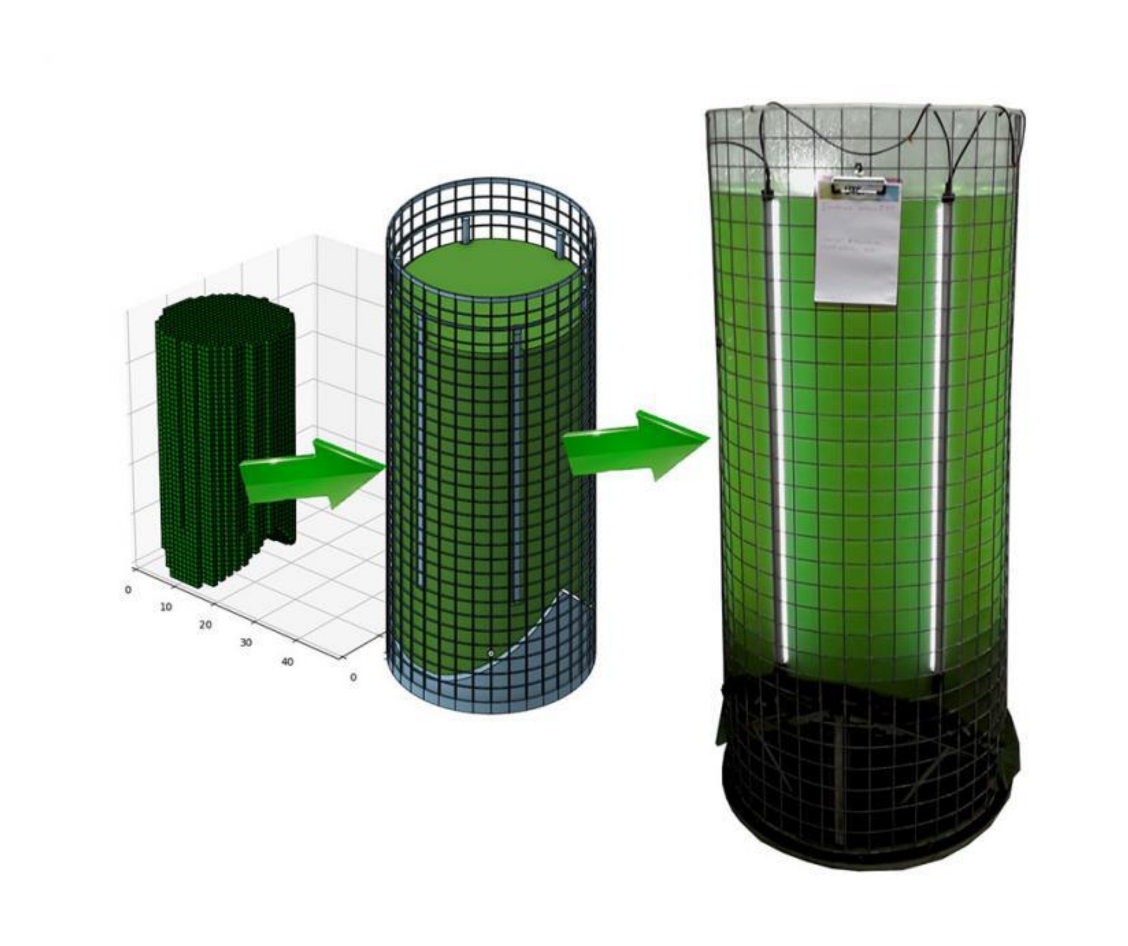
1 Demonstrate that MELiSSA is feasible as a LSS

(fulfill functions ? and recycling efficiencies)

Compartments studies, models & modelling objectives



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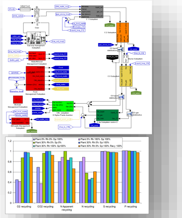
1 Demonstrate that MELiSSA is feasible as a LSS (fulfill functions and recycling efficiencies)

2 Sizing the compartments for the loop (scale-up)



Compartments studies, models & modelling objectives

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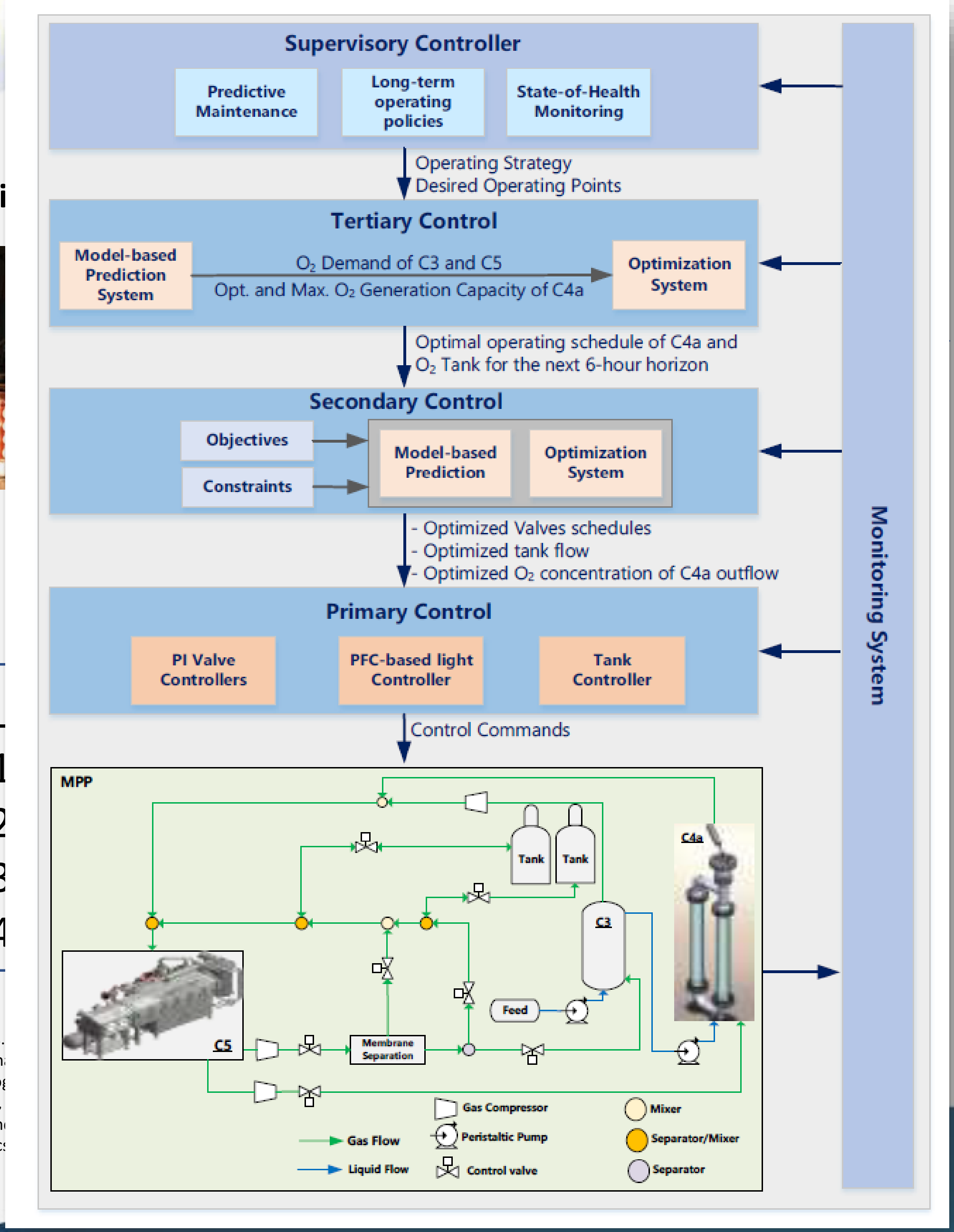

L
1
2
3
4

CREDITS :
1 : https://www.uts.
research/climate-ch
x-algae-biotechnolog
2 : C. Cuirans et al. ,
Ecosystems – Expan
Industrial Electronic

Understanding (gain knowledge)
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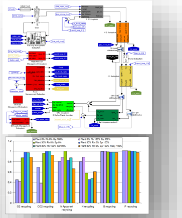

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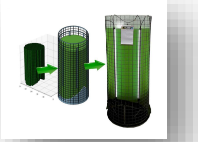

2 Sizing the compartments for the loop (scale-up)

3 Operation and control of the loop (dynamic modelling and physical system)

udies, models & modelling objectives

Understanding (gain knowledge)

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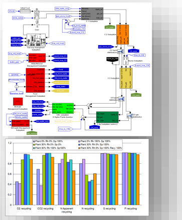

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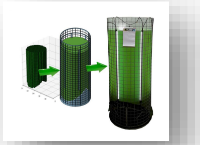
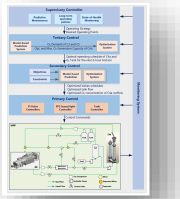


3 Operation and control of the loop (dynamic modelling and physical system)



4 ALiSSE criteria (sizes; efficiencies)

2 ongoing projects around models and control of complex systems

OSCAR (**O**ptimal **S**ystem-in-system **C**ontrol & **Ar**chitecture)

- Establish an organisational structure for developing knowledge models and control of LSS architecture
- Account for mass and energy balances
- Develop models of kinetic rates, both for physical and chemical and biochemical rate-limiting processes
- Interface the results of simulation with experimental information and strategy of control in the context of mission scenarios

VARSITY (**VAR**iu**S** **I**ntegration of system s**T**ud**Y** for model based cybernetics for the control of complex systems)

- Review (and update) of the current mathematical models of the MELiSSA compartments
- Define a logic and mathematical model for the loop as a network of the different compartments connected by mass and energy exchange through thermal, bio and chemical processes
- Study, trade-off and elaborate an overall control strategy on the connected loop
- Improve the ALISSE tools as well as its deployment with the Mars Transit Phase

What models are we talking about in MELISSA?

Static model: it gives the status of a system at a time t.

Dynamic model: the output of the model is a function of time.

Surrogate model: For a given range of input conditions, a surrogate model provides suitable approximations of the complex model with the suitable level of accuracy. (CFD model → N-tank in series model ; metabolic pathway model (FBA) → stoichiometric equation)

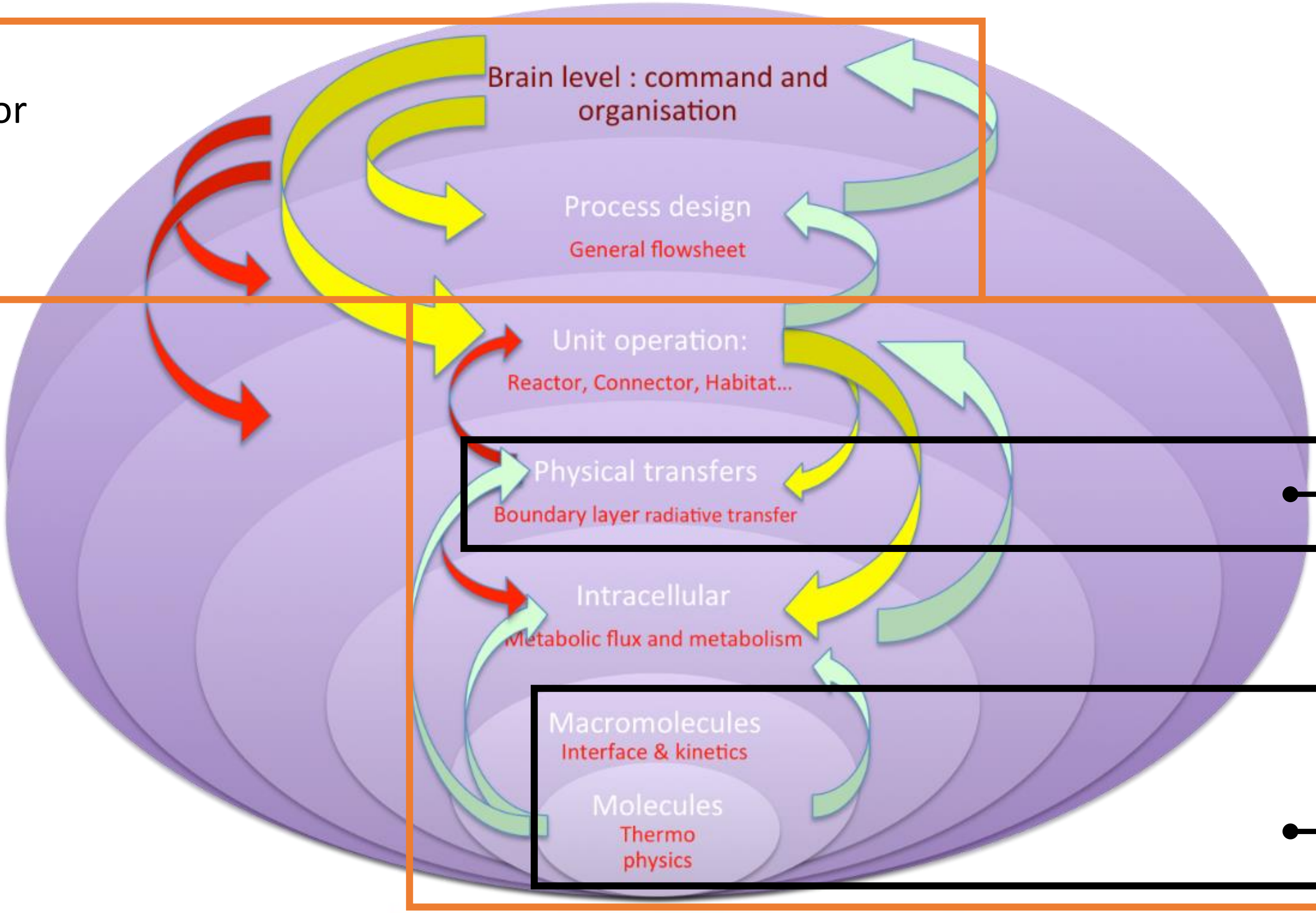
Numeric model: Numerical translation (software/languages) of mathematical-knowledge models

Topologic model: it is mandatory for assembling the different parts of the system and describe matter flow, energy flow and information flows.

Control model: Their study is associated to topologic model (of the complete system). They include the definition of operating constraints, manipulated variables and action variables. They can be developed on the basis of the knowledge model to obtain predictive control models.

Knowledge models and the division of a process in subparts

Layers 6 – 7 are for Loop / control / conception



Layers 1 to 5 are for models of compartments or unit operations

Common physical/thermodynamic laws and properties must be used for all compartments, to ensure the same description of all subsystems when integrating all models together

Where we are ? How to evaluate the MELiSSA models ?

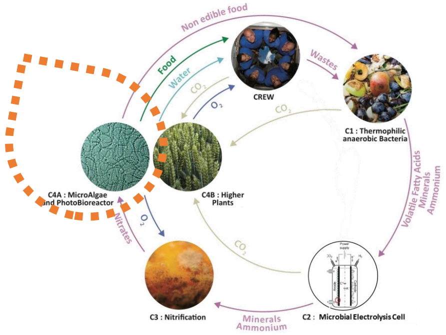
Model **R**eadiness **L**evel

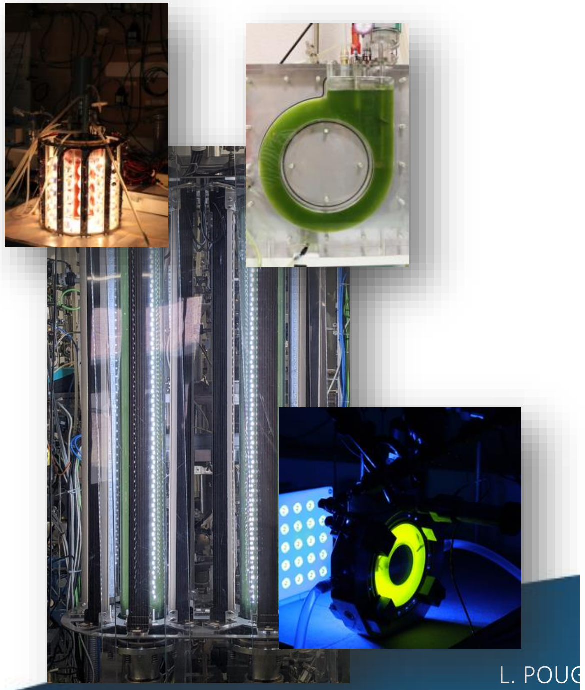
DEPLOYMENT	9	Model validated at operational scale with the required accuracy and confidence for the required range of variables
DEPLOYMENT	8	Model demonstration at relevant scale
DEPLOYMENT	7	Model validation and demonstration at different scales: lab scale, pilot scale
DEVELOPMENT	6	Numeric model analysis: sensitivity analysis
DEVELOPMENT	5	Numeric model calibration: identification of unknown parameters
DEVELOPMENT	4	Development of the numeric model: I/O vectors, variables, parameters
RESEARCH	3	Formulation of the assumptions and hypotheses of the model
RESEARCH	2	Establishment of the general theoretical framework and approach
RESEARCH	1	Definition of the general characteristics and objectives of the model: range of applicability, requirements, knowledge, scale-up and down

[predictive] **C**ontrol **M**odel **R**eadiness **L**evel

DEPOYMENT	9	Control Model proven at system (LSS) level
DEPOYMENT	8	Control Model demonstrated in integrated operationnal environnement : integrated in spaceflight LSS
DEPOYMENT	7	Control model demonstrated in operationnal environment : spaceflight of the system controlled
DEVELOPMENT	6	Control Model demonstrated in integrated operational/relevant environnement : integrated in lab/relevant LSS
DEVELOPMENT	5	Control model demonstrated in lab/relevant environment : limited to the perimeter of the system
DEVELOPMENT	4	Control-model development – systems/hardware/software integration
RESEARCH	3	Numeric system model demonstration in lab/relevant environment (calibration/validation)
RESEARCH	2	Numeric (informatic) theoretical system model development
RESEARCH	1	Mathematical theoretical-system formulation of the model : Variables(action/measured/predicted) ; perimeter / level of description; Theoretical analysis of the system of interest

Model review for MELiSSA knowledge and control : C4a





Process :

Air-Lift photobioreactor – characteristic time : ~ 100 h. – size ~ 100L /1 man (5-10% of O_2 needs)

Functions :

Oxygen producer , CO_2 consumer , Food (spirulina) producer

Model status [MELiSSA] :

Dynamic model : [PhotoSim] – *L. indica* (spirulina) growth in autotrophy (Nitrate or Ammonia source) + Light transfer model 2-flux surrogate model (flat or cylindrical reactor) + perfectly mixed reactor / Air-lift MPP reactor / Membrane photobioreacor
MRL : 8-9
Usage : Compartment simulation/control ; Complete loop steady state ; partial loop (C3+C4a+C5) dynamic and control model ; small size microgravity reactor (ArtemISS)

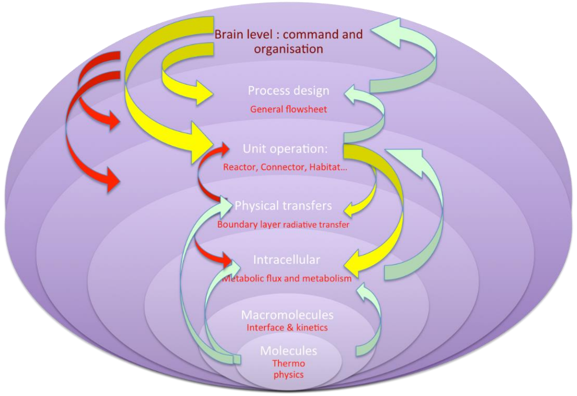
Current development :

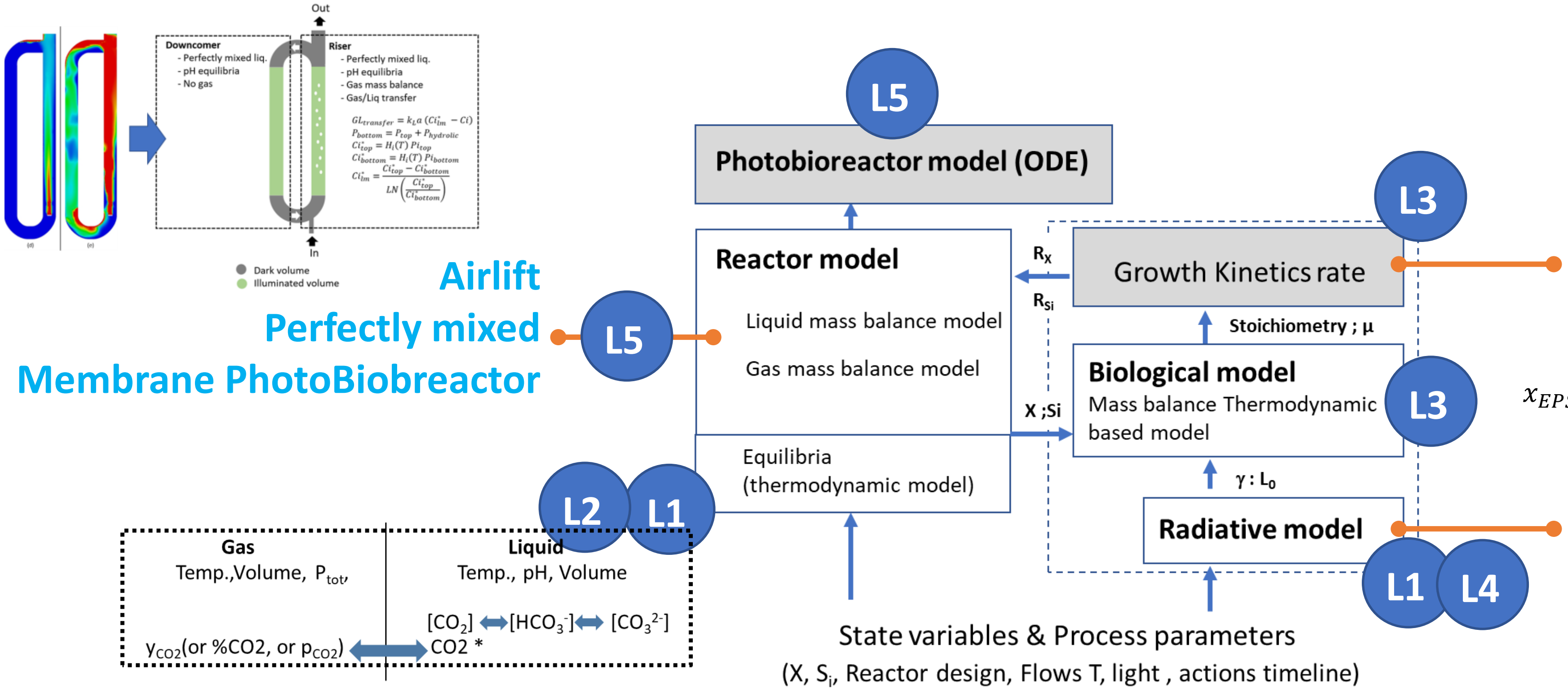
Update of model for LED – High flux + Air-lift
Upgrade for mixed N sources (Nitrate+Amonia+Urea)

Bottleneck for modelling (not fully solved) :

Lower Growth/productivities predicted with the new air-lift design (LED + High light flux + low residence time)

PSIM.M (namely PhotoSim) and the 7 layers structuration





Biokinetic coupling

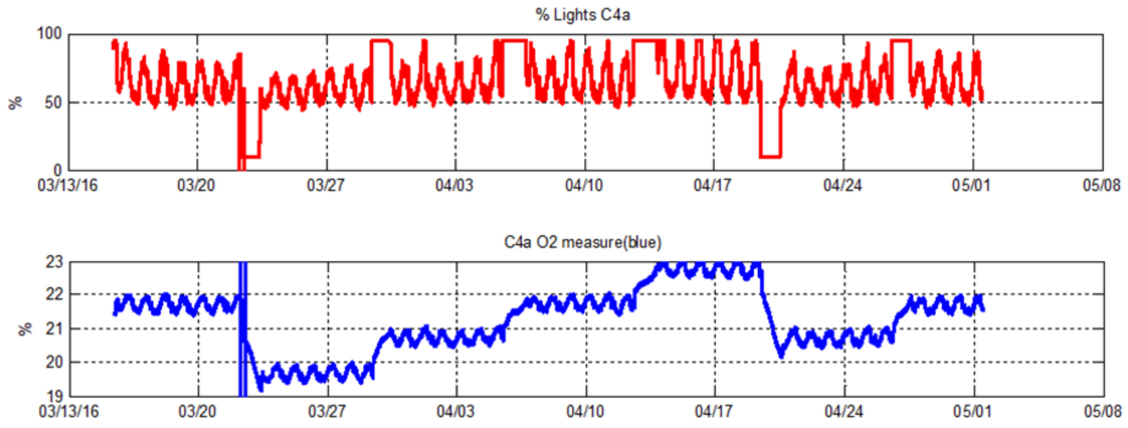
$$\langle r_x \rangle = (1 - f_d)\, \rho_M\, \Phi\, K\, Ea\, \gamma\, \bar{\beta}\, X$$

$$x_{EPS} = 1.33\left(\frac{P}{2e^-} - 1.23\right);\quad \frac{P}{2e^-} = f(\beta)$$

Two flux model

$$\frac{G_r}{q_0} = 2\left(\frac{n+2}{n+1}\right)\frac{I_0(\delta r)}{I_0(\delta L) + \alpha . I_1(\delta L)}$$

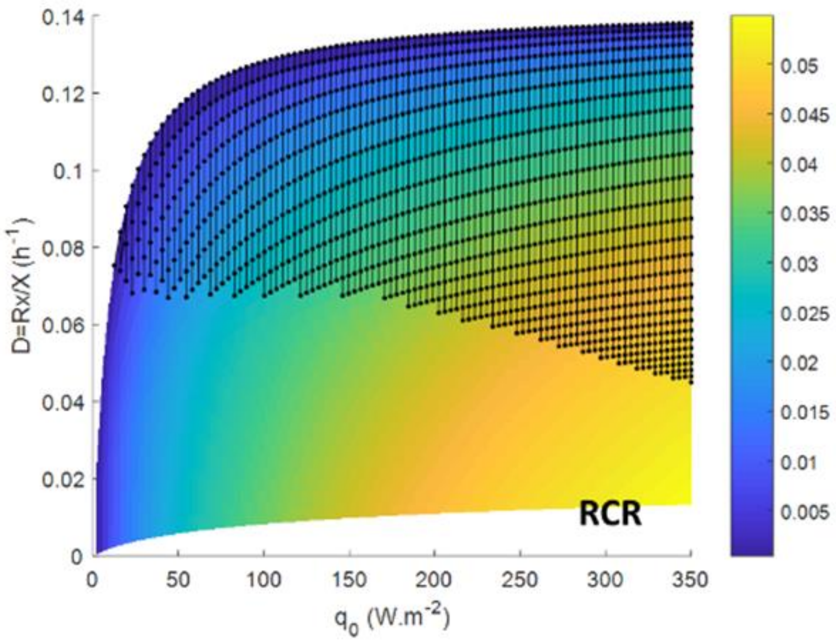
$$\bar{\beta} = \frac{1}{\gamma}\left(\frac{1}{\pi R^2}\int_{L0}^{R}\frac{Gz}{K + Gz}dz\right)$$

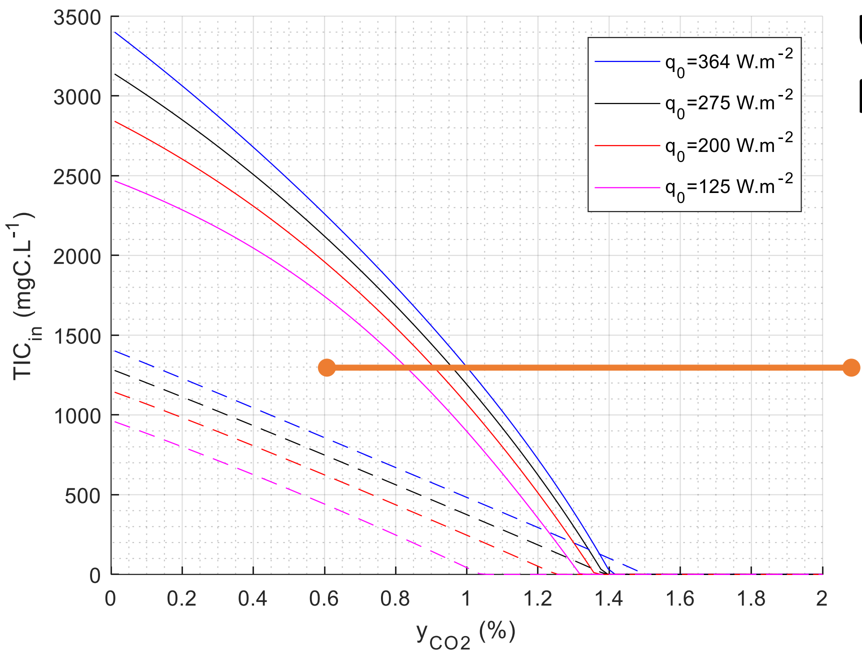


Usage : ligth control C4a-C5 (at various O2 setpoints)

[Credit : sherpa]

Usage : O2 productivity prediction





Usage : operating ranges for PBR

Predicted operating conditions (input gas y_{CO2} and input liquid TIC) to keep for the MPP Air-lift at HRT = 100h and pH 9.5 and recycling atmosphere for a 3 rat mock-crew

operation shall be :

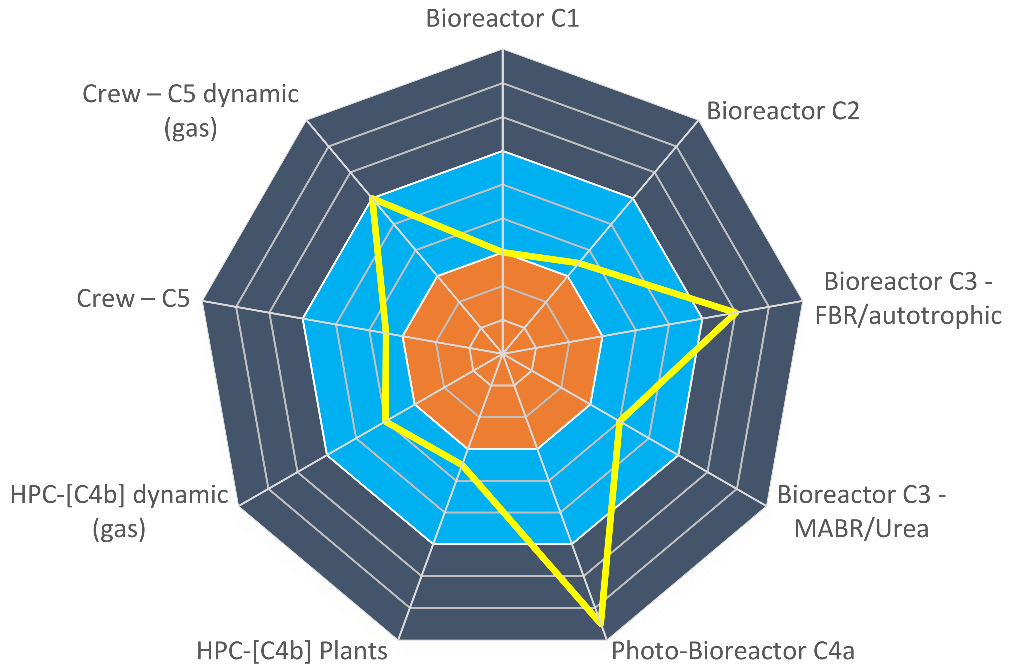
- above dotted line to avoid C-limitation (limiting factor >0.85)
- below plain line to have < 0.2% y_{CO2} at output.

Models review for MELiSSA knowledge and control
(fast summary)

Model status

	Process	Function	Static	Dyn.	Usage	Dev.	Bottleneck
C1	An. Thermo. Digestor / Membrane	OM --> VFA+CO_2+NH_3	✓	✗	Loop Steady State	Consortium caracterisation; Meta omics ; Thermomel	Feed complexity ; Consortium evolution ; Reactor heterogeneity ; SS instability
C2	An. MEC	VFA --> C02 + H_2	✓	✗	Loop Steady State	Hardware ; experiments ; Dyn. Model.	
C3	Aero . FBR	NH_3 --> HNO_3	✓	✓	FBR & Loop Steady State & dyn & control	Aero MABR	
	Aero . MABR	Urea --> HNO_3	✓	✗	Loop Steady State	Dyn. MABR	Biofilm<>Membrane
C4a	Aero. PBR	O_2/CO_2; food;	✓	✓	PBR & Loop Steady State & dyn & control	Update for LED High Flux - High HRT	deviation for LED High Flux - High HRT
C4b	HPC	O_2/CO_2; food;water	✓	✓ ✗	Sim Loop Steady State	Plant Characterisation Units ; coupling Gas dyn<>plants growth ;	
	HPC Gas	Gas exchanges & flows		✓ ✗	HPC gas exchanges dyn		rate limiting processes microgravity ; root/shoot connected models

Models review for MELiSSA knowledge and control *(MRL)*



Models with MRL > 4 -5 usuable for control models

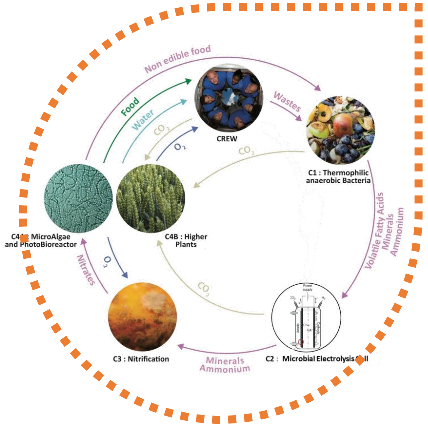
C4b (photobioreactor) and C3 (FBR nitrification) fully develloped

In devellopment/improvement : C2 , C3-heterophic/MABR , C4b

In term of mechanistic/predictive modelling C1 is the most complex one (even if anaerobic digestion is a well known process)

MELiSSA loop

Static model for the full loop (*with former C2 compartment*)

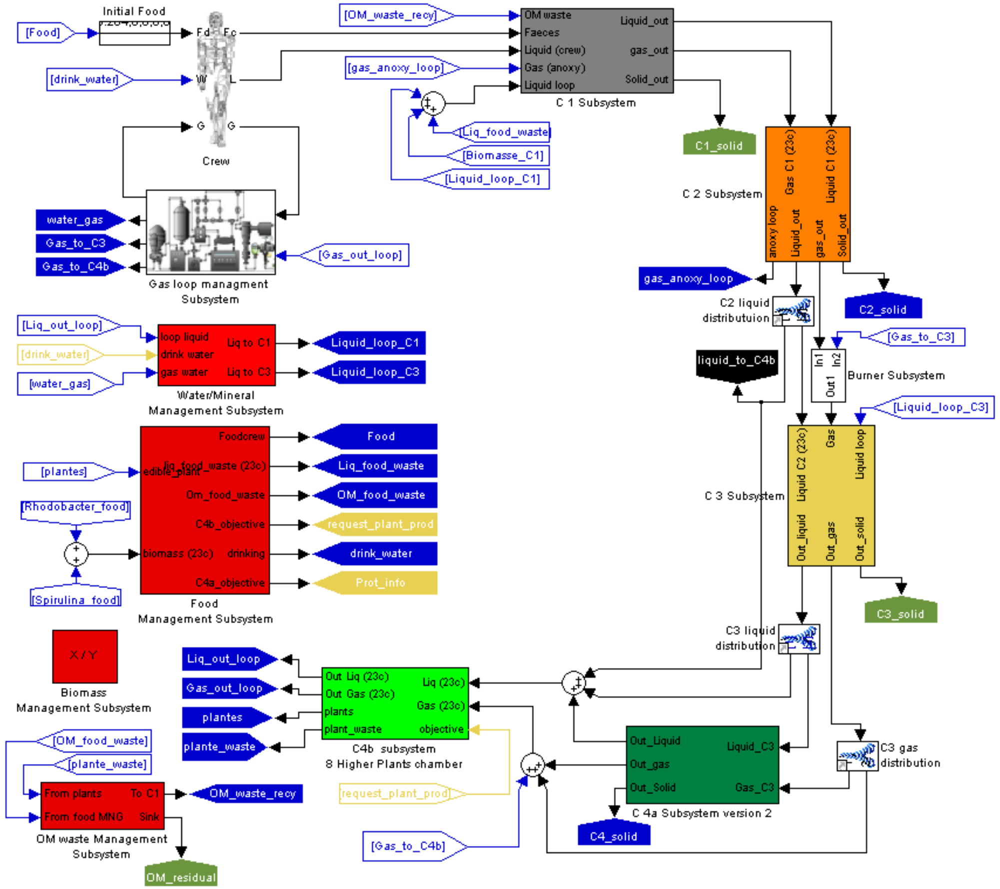


Gas management

Liquid management

Food management

Waste management



Model status [MELiSSA] :

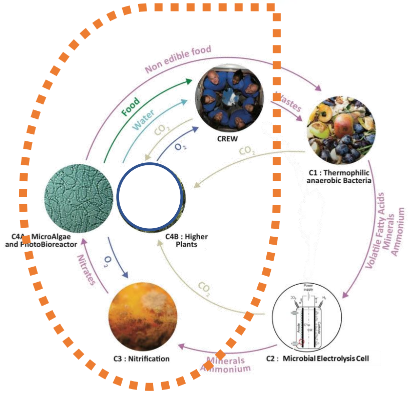
Usage : scenario / efficiencies / sizes (volume of reactors)

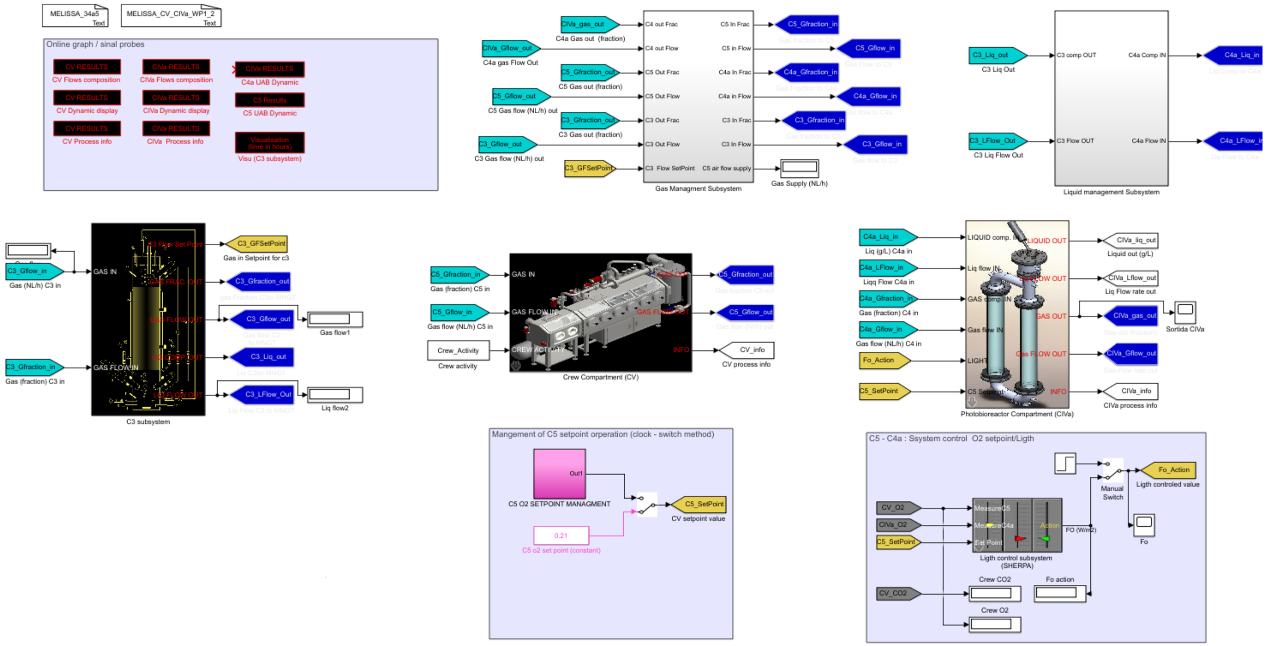
Current development :

Refurbishing of the structure (state vector / models + surrogate models / introducing dynamics model and 1srt order models for mass balance models)

MELiSSA loop

dynamic model for the partial loop (C3+C4a+C5)





Model status [MELiSSA] :

Usage : built in parallel with the MPP integration steps – control strategy + definition of functional tests of the loop

Current development :

Refurbishing of the structure (state vector / models + surrogate models / introducing dynamics model and 1srt order models for mass balance models) → toward a tool for both dynamic and steady state, integrating the MELiSSA model whatever is itscurrent devellopment status

MODEL STRUCTURATION AND REVIEW FOR MELiSSA KNOWLEDGE AND CONTROL.

THANK YOU.

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