Comprehensive modelling and simulation, reliable sensors and multilayer control strategy:

the essential system tools for a sustainable bioregenerative LSS.

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MELiSSA workshop

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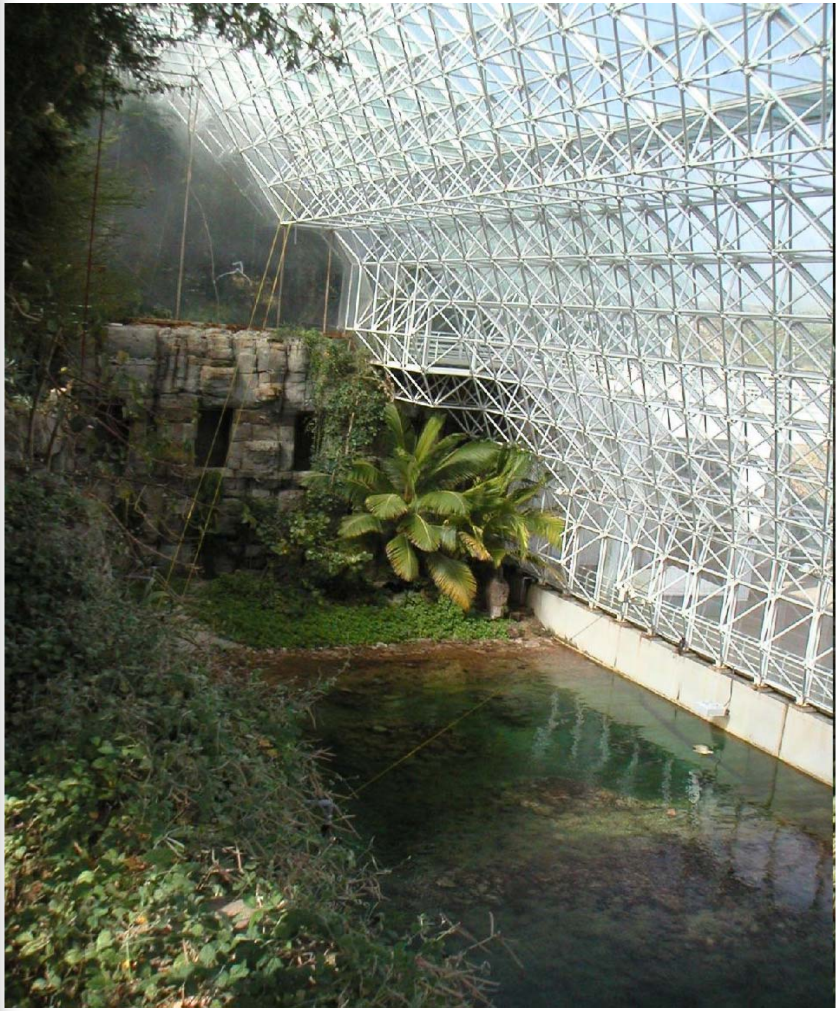
A self organising system



- Provide the system with mechanical, thermal and radiative energy
- Initialize the system with an earth-like ecosystem: 5 different biomes
- Let the system evolve by itself, acting on input energy variables and on some interactions between subsystems

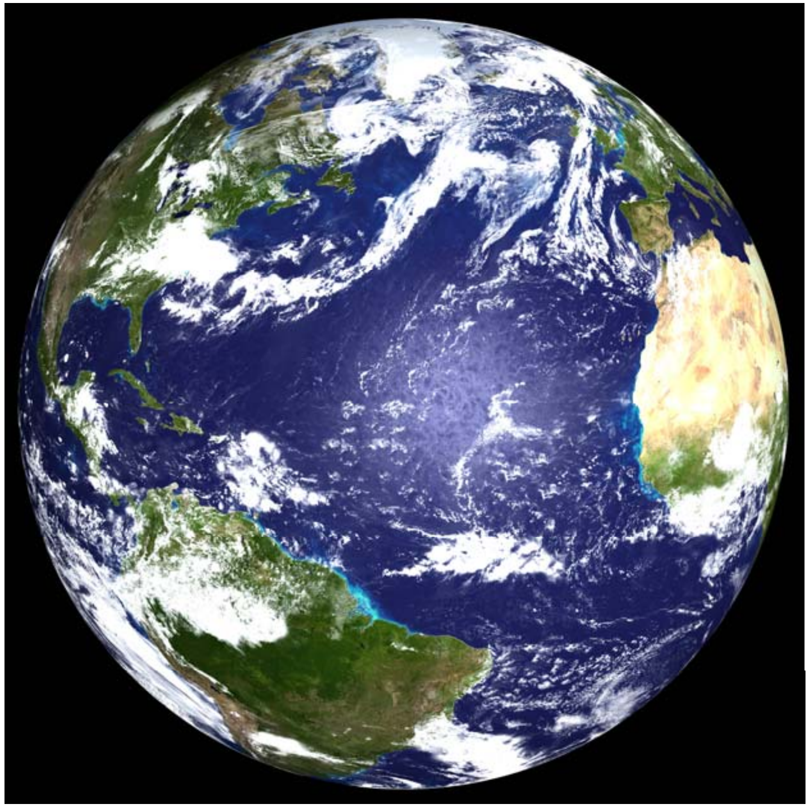
Biosphere 2 : main lessons (1)

- Two-year closure experiment (8 persons)
- Gas tightness of the system proven
- 83 % of diet produced by the system
- Average CO_2 : > 1 000 ppm… up to 4 000 ppm
- High daily CO_2 fluctuations : *ca* 600 ppm
- Progressive decrease of O_2 : down to 14.5 % after two years of experiment
- Sharp decrease in biodiversity

Biosphere 2 : main lessons (2)

- Photosynthesis does not equilibrate respiration “naturally”
- Respiration of soil is an important phenomenon
- Difficulty of control of CO_2 level, in spite of the use of physical adsorbers
- Biodiversity must be up kept by external means
- Insufficient understanding of subsystems interactions

Another self organising system



- 3.5 Billion years evolution
- Huge amounts of stocks
- High biodiversity
- Stochastic control
- Interactions between biomes not fully understood
- Long term evolution questionable

Manmade ecosystems

Engineered systems

- Assembly of subsystems with defined functions
- Strong interactions between subsystems and loop-based and feed-back topology
- Several levels of control and knowledge necessary

⇨ How can we cope with this complexity, issued from a loop architecture?

Special case of LSS for space

- Space LSS are complex: no availability of free resources; necessity of high degree of closure saving all resources: matter & energy
- Very integrative to minimize the mass, volume, energy, crew time, compacity, risk
- Air, water, food loops are tightly coupled
- Need of high level of knowledge, science, technology, control, information
- Need of model-based System Engineering upon the life cycle for assessment of reliability, stability.
- Need of exchange of information (storage, encoding, transfer, etc.)

Fundamental properties of LSS

- "Systems in systems" general topology
  - Something to do with fractal geometry
  - The part must 'account for' the global objective

- Non unidirectional flowchart
  - Multiple retroactions
  - Feedback control
  - May generate instabilities

Solution

- Bring rationale understanding
- Bring intelligence
- Bring control

Do not wait for stochastic control

The new deal

- The 3 former statements are not an option, they are mandatory for any LSS

- The new deal is that it has become obvious that these statements are also mandatory for ensuring sustainability of Earth ecosystem

MELiSSA possesses this precursor approach

Towards epistemology

What is a model?

- If a model supports intelligence (rationale understanding) it contains some generic rules of description: basic principles

- ‘Knowledge’ models are the only way ahead, although difficult

- The vehicular language is often mathematics, but not always

What are the basic principles

- Elements conservation: stoichiometry and mass balances
- Energy conservation principle: first law of thermodynamics
- Momentum conservation: Navier Stockes equation

These are the tools of chemical engineering

But….

- It is not totally sufficient…
- Statistical physics has brought some intrinsic uncertainties
- …Leading to principle of irreversibility… to quantum mechanics…
- Similar examples with molecular genetics

Lessons

- We have to cope with statistical behaviours at the smallest scales…

- But statistics is not stochasticity

Overview

MELiSSA and LSS research is part of the history of philosophical ideas

Humanism, Blaise Pascal, Galilée, Copernic, Descartes, Spinoza, Leibnitz, Enlightenment century, Emmanuel Kant, Carnot, Gibbs, Boltzmann, Darwin, Bergson, Maxwell, Planck, Heisenberg, Shannon, Fermi, Dirac, Pauli, Schrödinger, Curie, Prigogine, Watson, Cricks, Monod…

This epistemological perspective is the clue for the societal success of these researches

Back to the practice (1): “systems in systems”

‘Systems in systems’: modelling principles

Mass balances for a set of compounds sorted and fixed

Stoichiometric description for the biotransformations

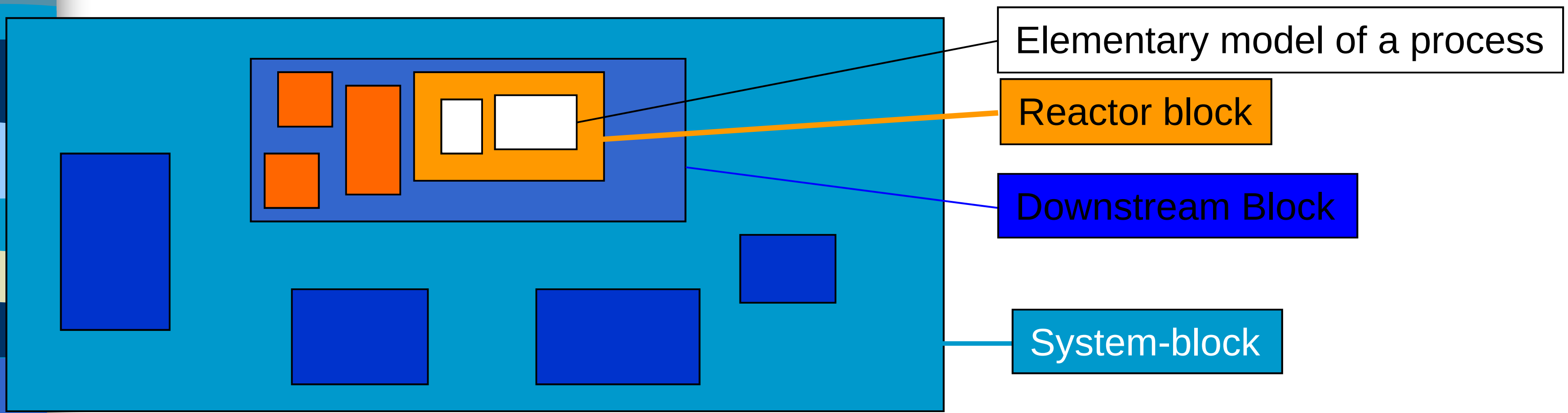
Two-steps simulation : at steady-sate then dynamic, including

Constraints (atmosphere, liquid, food…)

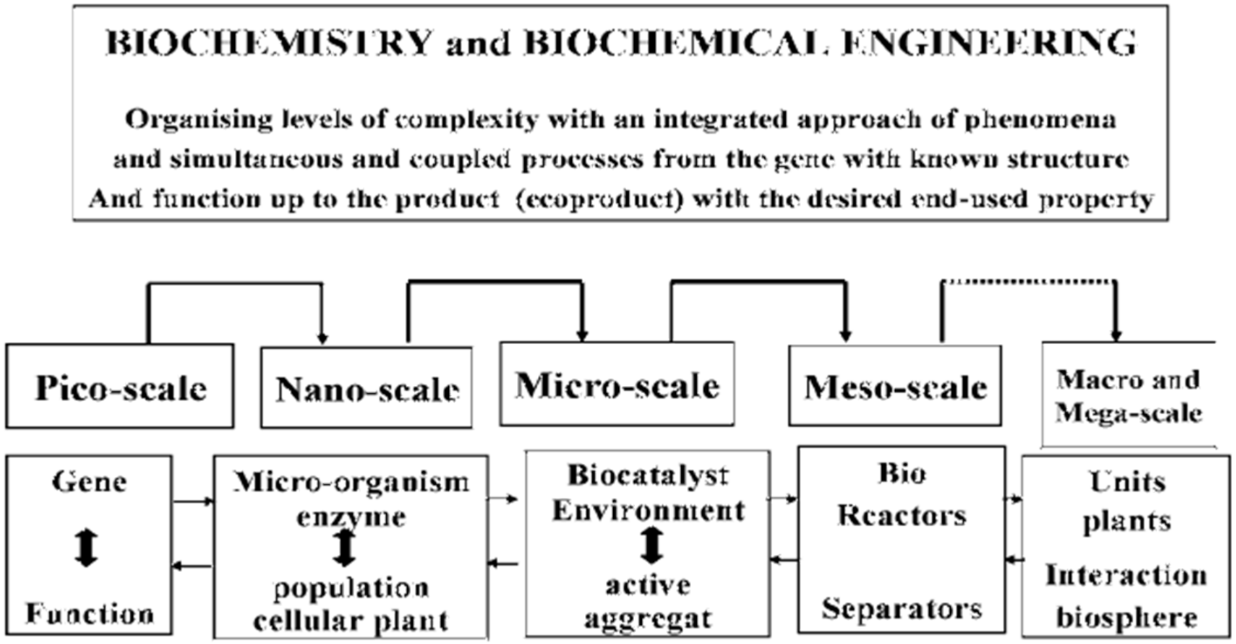
Loop operating parameters (waste recycling, flow dividers,…)

Different choices for linking/operating subsystems

Approach by successive layers



Organisation of levels of complexity



4 levels of biological organization

Genome
[DNA]

Transcriptomic
(transcription)
[RNA]

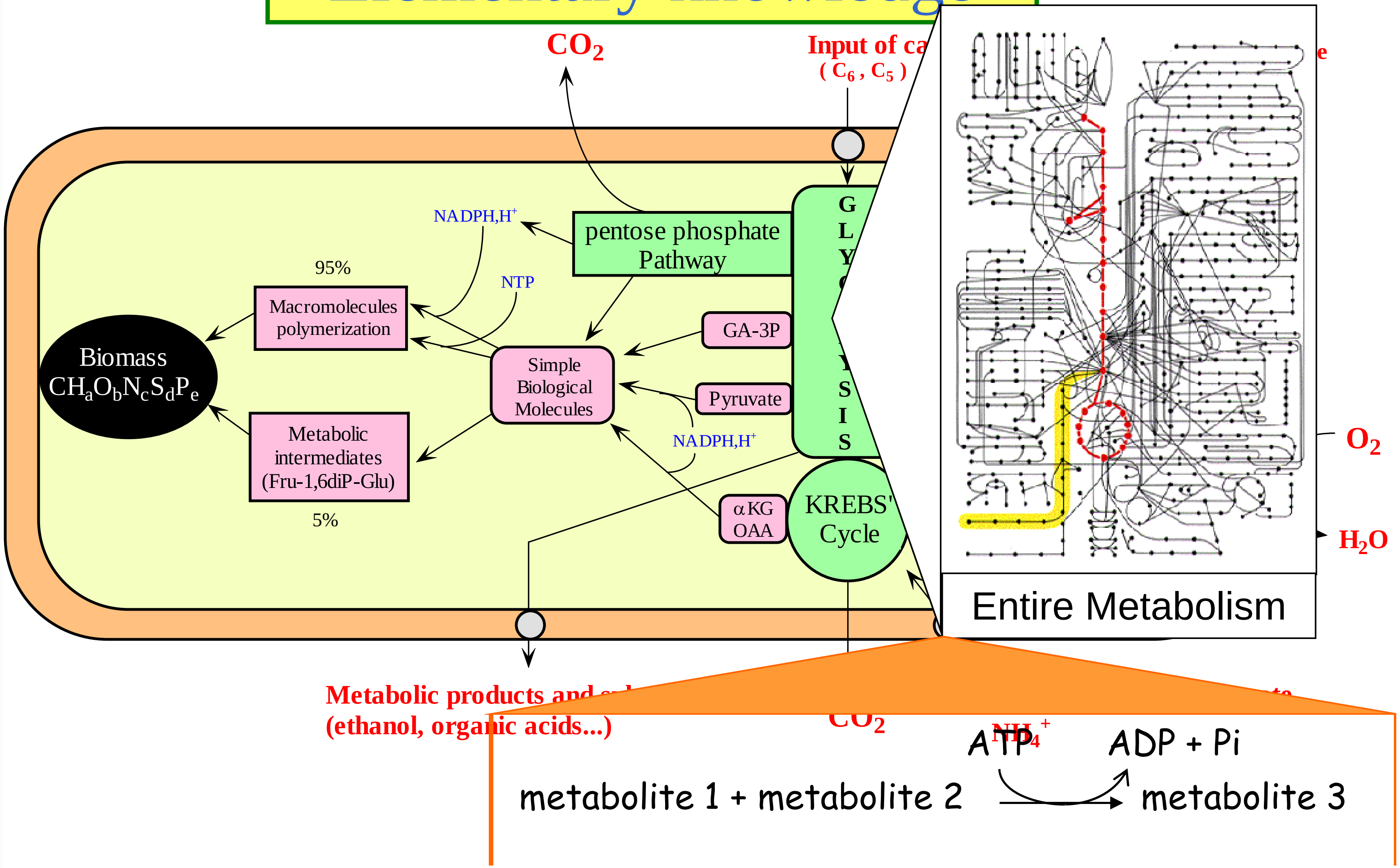
Proteomic
(traduction)
[Proteins-Enzymes]

Metabolomic/Fluxomic
(metabolism)
[Metabolites-reactions]

Phenotype
(observations)

Level 1	Level 2	Level 3	Level 4
Functional genomics		**Metabolomics**	**Physiomics**
Genetic expression	Proteomics, bioinformatics	Metabolic reactions and fluxes	Inter relations cell-environment

Elementary knowledge



Two possible determinisms: no physical limitation

- The metabolism "chooses" the maximum specific growth rate μ_o and the yields. The substrates are converted into living matter and other sub-products given the intrinsic regulation of the metabolic rates
- Substrates availability (and products inhibition) lead to phenomenologic rates such as

$$\mu = \frac{\mu_0 \cdot S}{K_S + S + \frac{S^2}{K_I}}$$

Two possible determinisms: physical limitation

- The rates are imposed to the metabolism by example by :
  - Gas transfer
  - Continuous operation
  - Radiation transfer
  - Thermal transfer…
- The biological rates depend on environmental conditions. The metabolism adapts its regulation space to the external rates with consequence for the yields

In progress

- Detailed analysis of energy conversion processes: enthalpy and entropy balances at reaction levels
- Analysis of metabolic coupling processes and energy conversion processes
- Direct prediction of the yields and of secondary metabolites production
- Understanding of coupling phenomena between physics and metabolome

Back to the practice (2): constructal approach

Constructal approach

- Introduced by Adrian Bejan (1995) for optimal engineering
- It states that any system is destined to remain imperfect, supporting entropy production
- The best that can be done is to optimally distribute the imperfections of the system (distributed entropy production)
- The constructal law is the principle that generates the least imperfect architecture possible
- Solution: the best way is to distribute the more resistive regime at the smallest scales of the system

What does-it tell us in terms of LSS architecture ?

Multi-scale approach is employed

- Imperfections must be distributed along the different scales
- Knowledge must be equally distributed from nano- to macro-scales

Consequences

- Even if entropy balances are difficult to examine at metabolic level, the resistive regimes are distributed at the smallest scales
- Macrobiome is ‘organized’ in the constructal way
- This is a consequence of the mandatory stability of microbial communities
- And… intelligence is related to the distribution of entropy

Back to the practice (3): sustainability

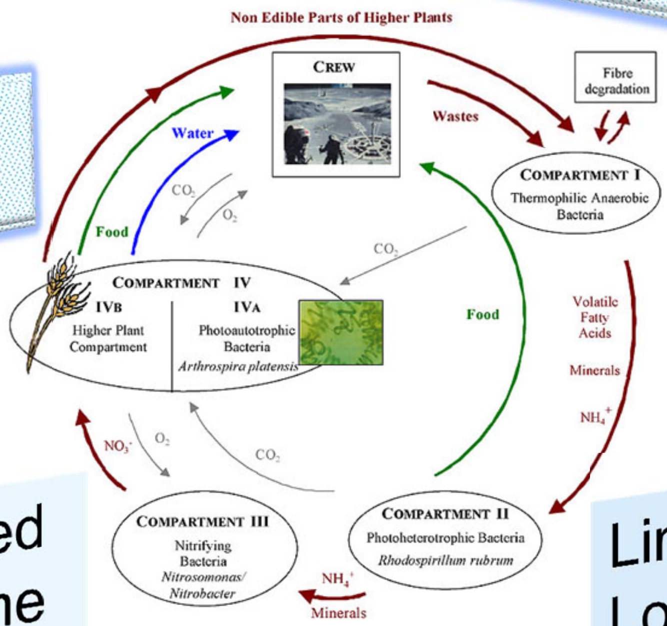
Sustainability of manmade ecosystems

- Intelligence is supported by predictive models
- Modelling must address all subsystems with the same degree of relevancy and imperfection
- Permanent status of the process must be recorded on-line (sensors development)
- Control strategy must be distributed: hierarchical control and predictive functional control (PFC)

COMPLEXITY

High Constraints
On Mass , Volume , Energy

HIGH DEGREE OF
CLOSED LOOP



MULTI ACTORS

High Level of
Reliability &Safety

INTERDEPENDANT
FUNCTIONS

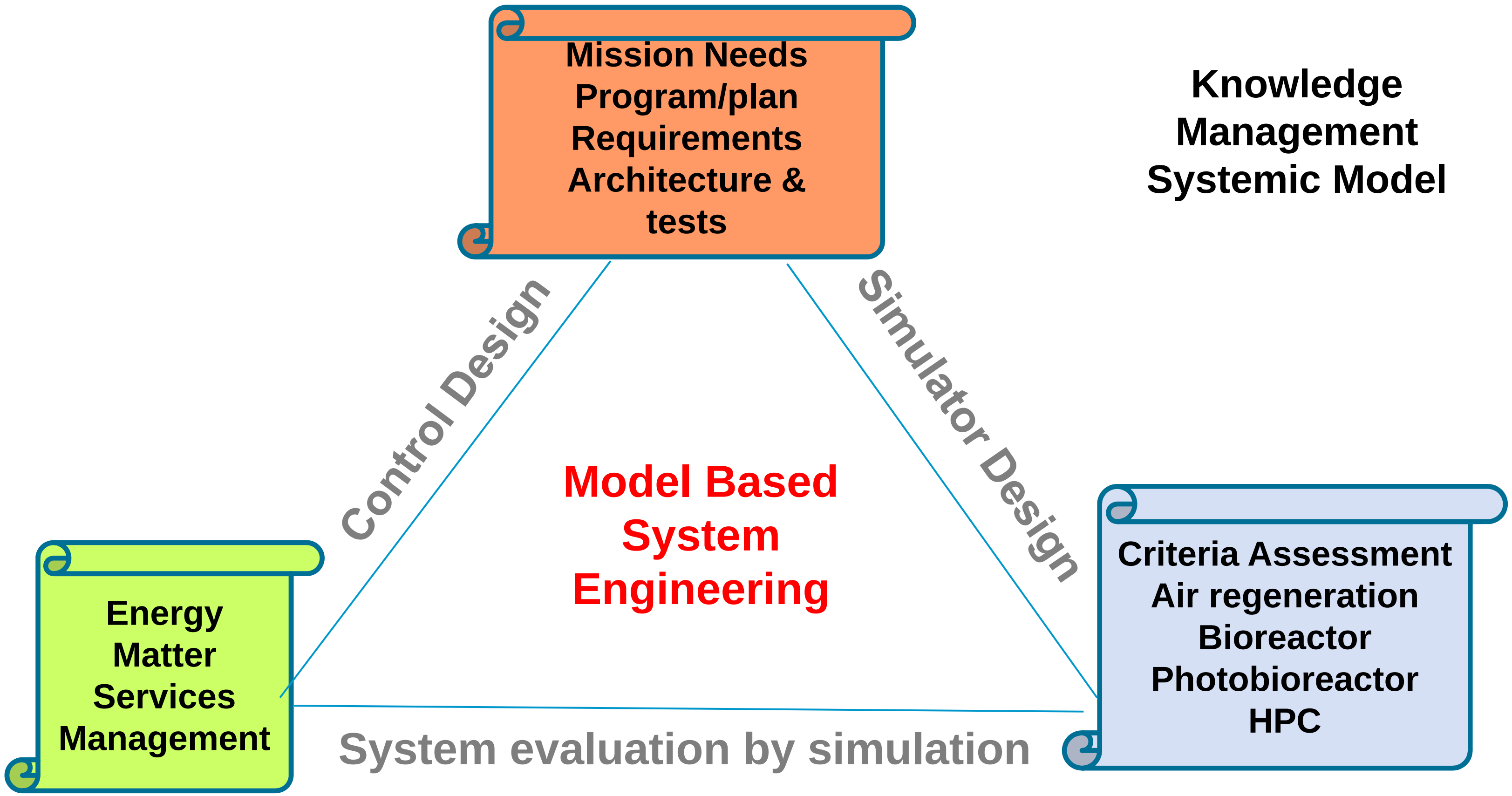
Restricted
Crew time

Limited
Logistics

Need for different types of model

(*From Sherpa Engineering, 2015*)

LSS requires a model-based integrated approach



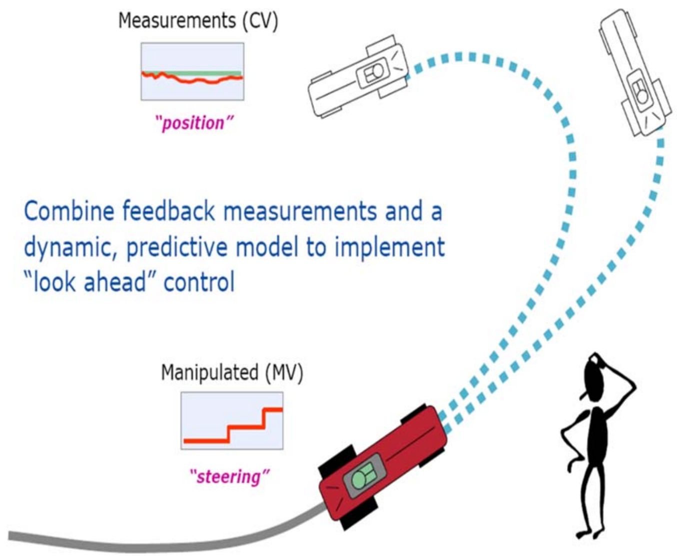
(*From Sherpa Engineering, 2015*)

LSS requires a model-based integrated approach

- Knowledge management
- Model-based predictive control: decision & supervision Model
- Multi-domains, Multi-ports & simulation tools

Model-based predictive control

- Model-based to take into account the complexity of interactions
- Predictive to anticipate and prevent the lack of resources and optimize the closed loop
- MELiSSA control: a closed control loop for a closed loop system



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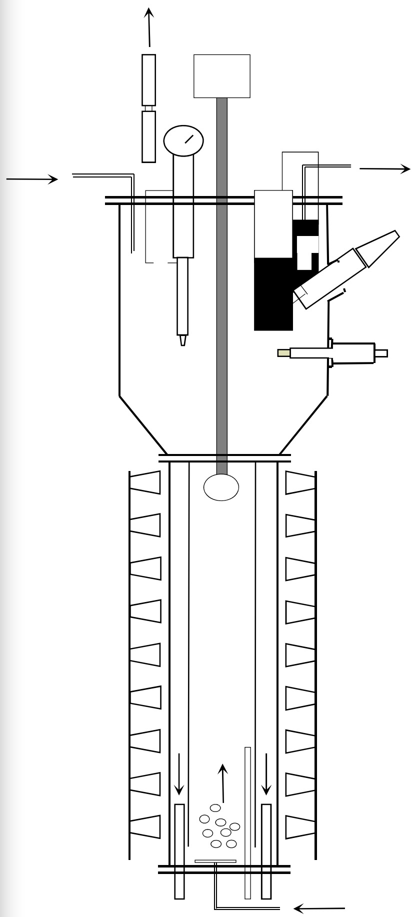
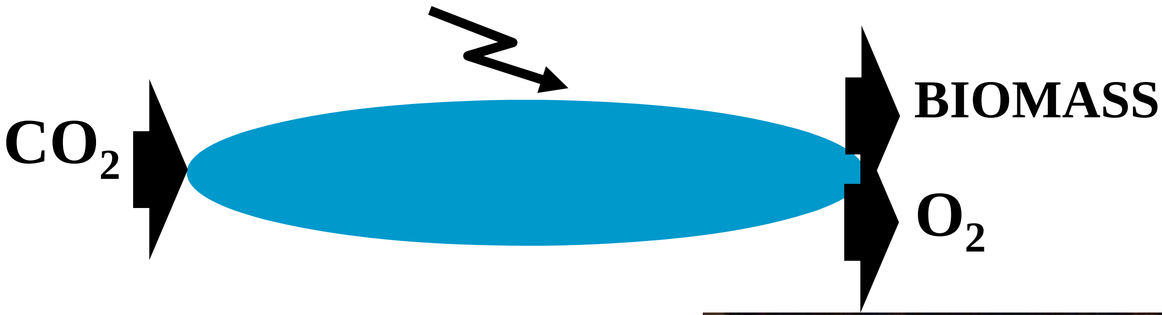
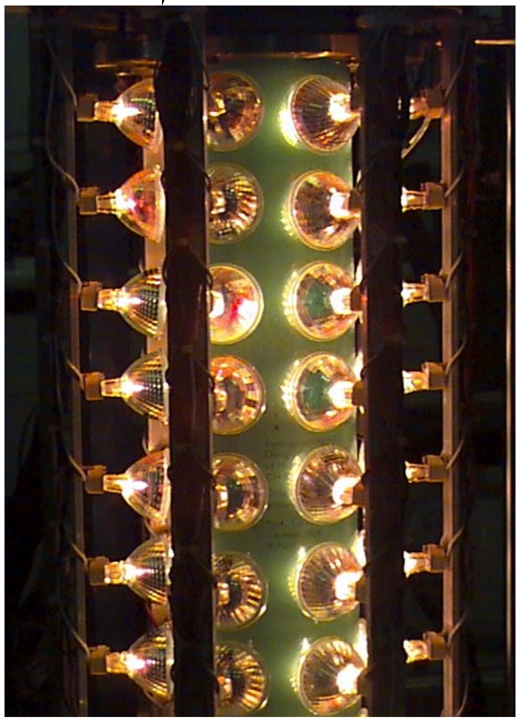
Back to the practice (4): experience

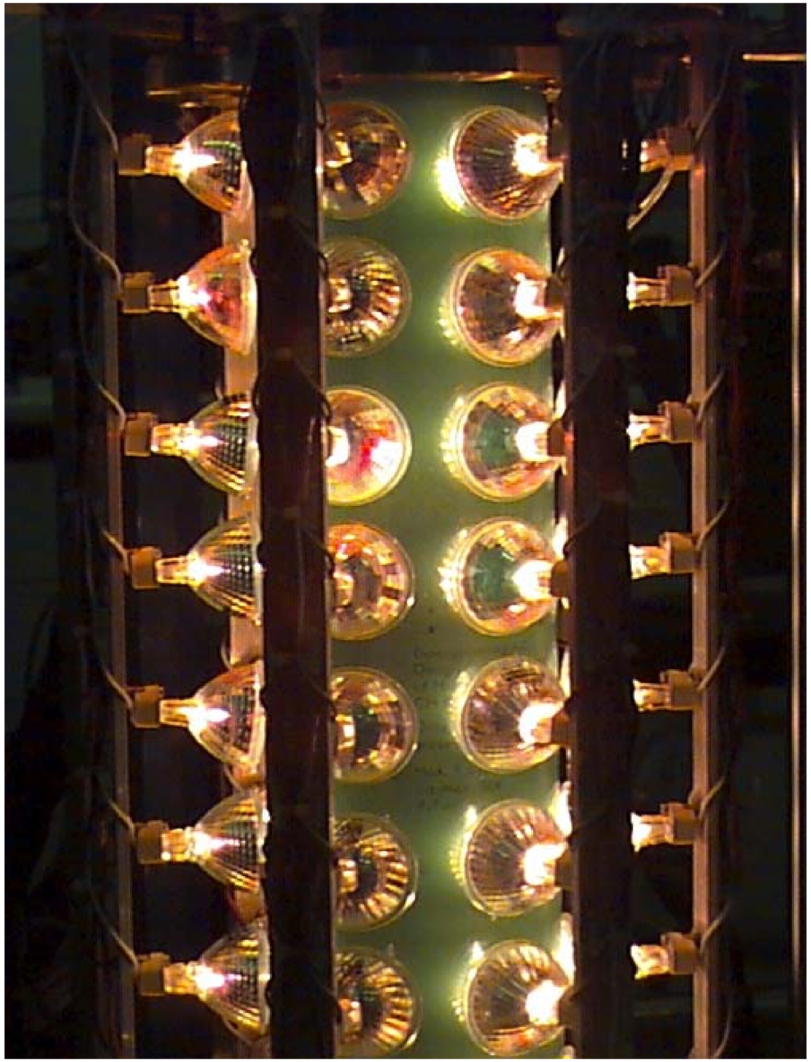
Arthrospira as O_2 producer





- Basic studies: strain, medium, etc.
- Complete math. modeling
- Design and installation of pilot reactor
- Continuous operation of the pilot reactor. Control.
- Scale-up
- Hydrodynamic characterization

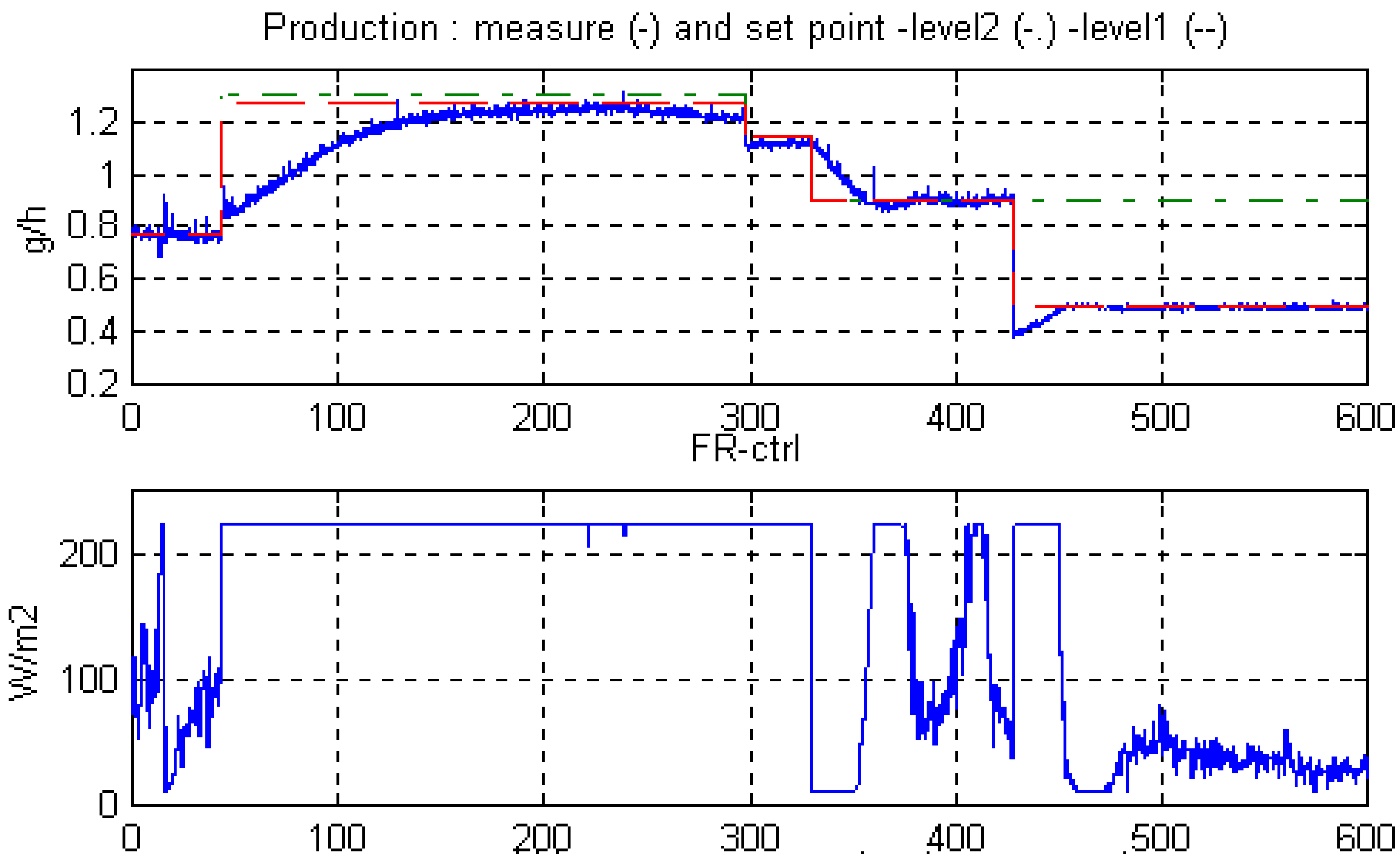




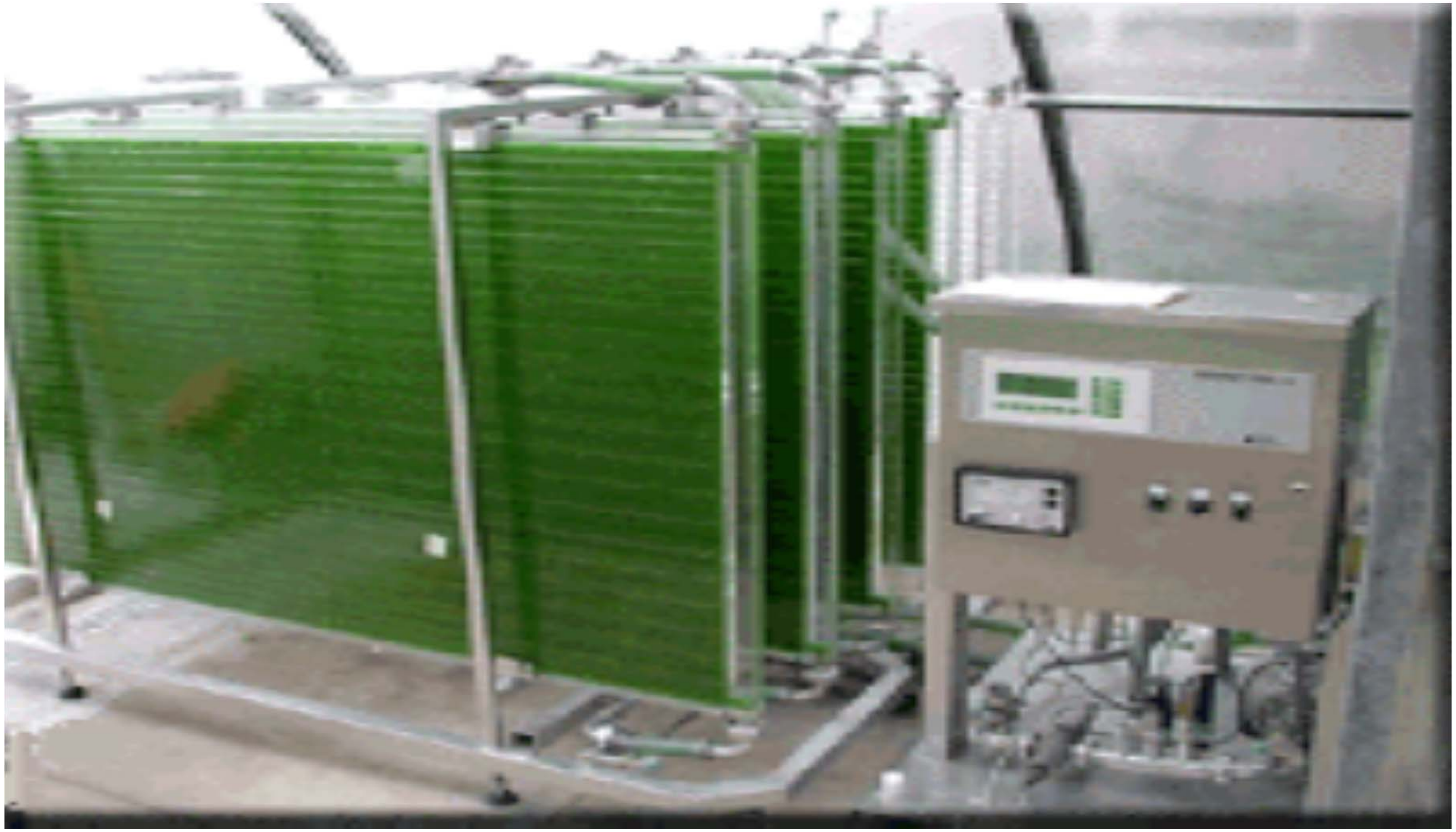
Application to light transfer limitation

- Light transfer is rate limiting in PBR
- Understanding of light transfer enables efficient control
- Variable biomass composition and productivity is understood and controlled

Arthrospira bioreactor predictive control



Bioreactor scale



Conclusions

- Nothing proves that self-organised biological system converges towards stability
- Constructal approach applied to model and control is a useful guideline for architecture
- Bioprocesses conception must include metabolic and genetic understanding in control strategies
- Developments of bioprocesses require also fine understanding of physical phenomena

Conclusion

Overall sustainability and reduction of size and time constants can only result from intelligence and understanding of local phenomena

Thank you for your attention

Important features of intracellular universe

- ATP pool inside the cell match 0.1 to 2-3 s needs of the cell
- Same time constants for most metabolic intermediates
- H^+ content inside the internal space of a mitochondrion is less than 1 to few molecules… only !
- Protein concentrations inside the active part of a μo may reach 500 gL^{-1}

- No accumulation of metabolic intermediates is justified

That we know

- Analysis of metabolic routes : topology, convex analysis (EFM…), metabolic pathways
- Calculation of metabolic fluxes on the basis of pseudo steady state for metabolic intermediates
- Analysis of the reversibility of metabolic reactions
- Drawing up of a metabolic map representative for an average functioning knowing the global yields and rates

- Good knowledge of metabolic topology but no real prediction of fluxes distribution