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Dynamic Aspects and Controllability of the MELiSSA Project: A Bioregenerative System to Provide Life Support in Space

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Abstract Manmade ecosystems differ from their prototype biosphere by the principle of control. The Earth Biosphere is sustainable by stochastic control and very large time constants. By contrast, in a closed ecosystem such as the micro-ecological life support system alternative (MELiSSA system) developed by the European Space Agency for space exploration, a deterministic control is a prerequisite of sustainable existence. MELiSSA is an integrated sum of interconnected biological subsystems. On one hand, all unit operations in charge of the elementary functions constitutive of the entire life support system are studied until a thorough understanding and mathematical modelling. On the other hand, the systemic approach of complex, highly branched systems with feedback loops is performed. This leads to study in the same perspective, with the same degree of accuracy and with the same language, waste degradation, water recycling, atmosphere revitalisation and food production systems prior to the integration of knowledge-based control models. This paper presents the mathematical modelling of the MELiSSA system and the interface between the control strategy of the entire system and the control of the bioreactors.

Keywords Bioregenerative life support · Closed system · Predictive control · Mathematical modelling

Introduction

Future mission goals require long-duration space flight, including the International Space Station which will accommodate international crews on-orbit for periods of at least 3 months;

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however, the ultimate objectives are the development of autonomous life support systems required for long-term manned missions to the Moon, Mars and beyond or to permanent Lunar or Martian bases. In this perspective, the required autonomy means that the system must ensure the capability of both recycling wastes (water, air and solid wastes) and producing food, water and oxygen.

The production of food with a suitable nutritional value for human being can only be achieved if some parts of the support system include living organisms (bacteria, higher plants, animals, etc.). These food-producing compartments interact with the global environmental control and life support system (ECLSS) environment not only because they are producing additional wastes but also because they are contributing to recycling functions such as air revitalisation (photosynthetic activity by example) and water recycling. This normally calls for a more systematic use of living organisms potentialities, both for food production and waste recycling functions. This leads to so-called regenerative life support systems, which enable to progressively reduce the use of physico-chemical transformations to specific unit operations such as phase separations, sterilisation of some flows or degradation of recalcitrant fractions of wastes.

Therefore, it can be stated that regenerative life support systems are the clue for ambitious long-term manned space flight missions of exploration or permanent bases, knowing that experience has shown that manmade ecosystems cannot be stabilised by self-control but by deterministic control in a process engineering perspective.

Micro-ecological life support system alternative (MELiSSA) is conceived as a tool for understanding the behaviour of closed ecosystems and developing the technology for a future regenerative life support system for long-term manned missions in space or on a lunar base [1]. The driving element of MELiSSA is the production of edible biomass, water and oxygen from waste (e.g. higher plants wastes, faeces, urea…), carbon dioxide and minerals with the use of light as a source of energy for photosynthesis. The loop model was based on the recovery process that can be found in an "aquatic" ecosystem. MELiSSA is divided into five compartments colonised by microorganisms and higher plants interconnected by different liquid, gas and solid flows. Each compartment is colonised by specific organisms and has a specific contribution to the overall transformation process. The sixth compartment is the crew (Fig. 1):

- Compartment I: liquefaction of wastes into volatile fatty acids by thermophilic anoxygenic acidifying organisms;
- Compartment II: removal of volatile fatty acids by photoheterotrophic anoxygenic *Rhodospirillum rubrum*;
- Compartment III: nitrification by a co-culture of *Nitrosomonas* and *Nitrobacter* sp.;
- Compartment IVa: nutrient and oxygen production by *Arthrospira platensis*;
- Compartment IVb: food and oxygen production by higher plants;
- Compartment V: crew

This ecosystem is conceived for producing food, water and oxygen by reprocessing a maximal part of the wastes produced by a human crew and by the higher plant chamber.

From an environmental systems perspective, the potential objectives are qualitatively as follows:

- Regeneration of air, water and food waste in a way that minimises overall logistical burdens, minimises demands on crew habitat resources, ensures habitability and promotes self-sufficiency and safety.

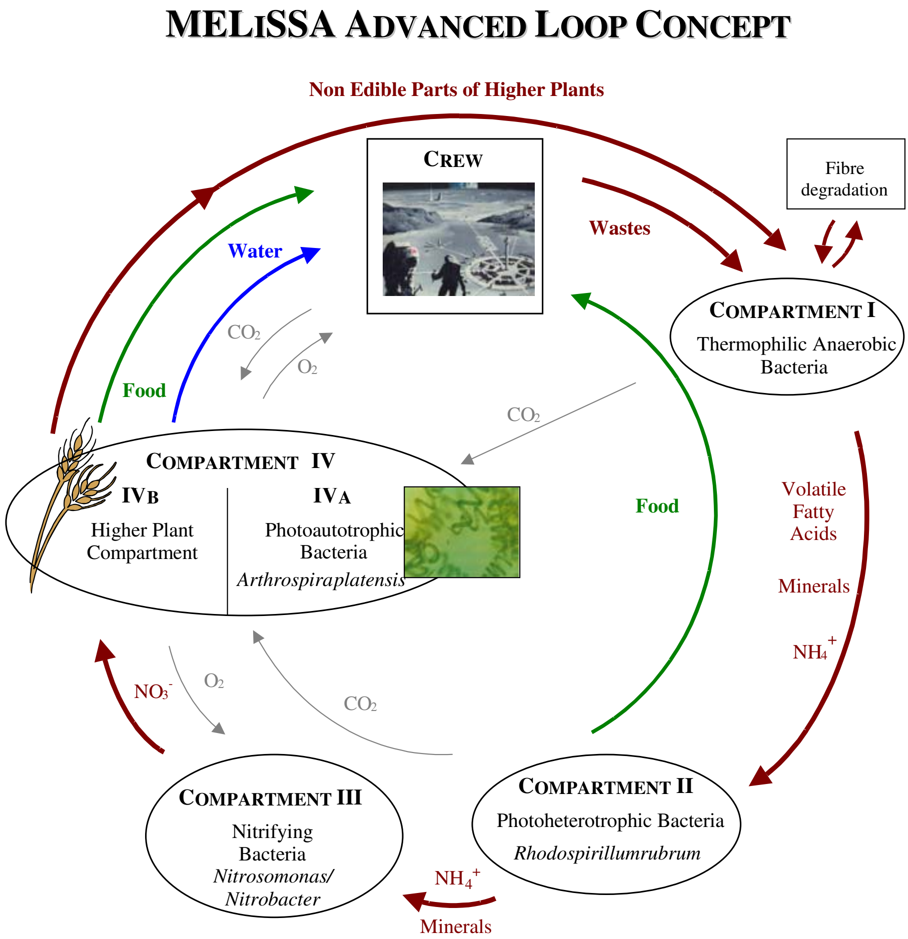

Fig. 1 Schematic representation of the MELiSSA loop

- Management and recycling of solid wastes to achieve optimum resource recovery, maintain a safe environment within the crew habitat and minimise solid waste storage and accumulation.
- Production of plants for the crew consumption with a goal of supplying up to 95% of a crew's food requirement.
- Effective environmental monitoring and control that precludes hazardous conditions (e.g. fire, toxic contaminants accumulation) and minimises crew involvement.
- Prolonged reliability of components and systems.

The quantitative requirements can be summarised as follows:

- O_2 production: 1 kg per person per day
- CO_2 removal: 1.2 kg person per day
- Drinking water production: 2.8 kg per person per day
- Food (freeze-dried + canned food): 2.7 kg per person per day
- Hygiene water: 13 kg per person per day
- Energy to remove: 15 kJ per person per day (approximately 170 W per person)

This leads to approximately 20 kg per person per day of different compounds to produce and eliminate for complete recycling [2–4].

Twenty principles for designing ECLSS are listed [5, 6]. Among them, five are primarily important:

1. ECLSS are inherently "closed chamber operations" which means that: (1) dilution is never the solution to pollution; (2) every exogenous product is consumable and (3) everything that is produced must be reprocessed.
2. Manmade ecosystems differ from their prototype biosphere by the principle of design. The sustainability of the Earth biosphere is ensured by its biological diversity, creating an intricate network of metabolic paths with fail-safe redundant functions by buffer stocks of inert biomass and the huge size of the planet itself. Such a system, produced by evolution, is sustainable by stochastic control. By contrast, in a closed ecosystem, all these functions become ineffective: its diversity, size and time constants are not sufficient for stochastic mechanisms to operate successfully. A deterministic control system is therefore a prerequisite of sustainable existence. This includes, at prime level, the following triptych: (1) measurement by reliable sensors, (2) scheme of control and (3) regulation. This brain-level of the manmade ecosystem is materialised by the mathematical deterministic modelling and simulation of the interacting parts of the system.
3. ECLSS must be conceived as an integrated sum of unit operations. This requires, on one hand, a systemic approach of complex, highly branched systems with feedback loops and, on the other hand, the study of a set of unit operations in charge of the elementary functions constitutive of the entire ECLSS.
4. The technologies must be studied in a generic way, considering that the solutions will depend on external constraints that are not presently completely fixed. This must start by progressively increasing the complexity (and the degree of closure) of the system, the design of which must be evolutive.
5. The need for improving in regenerative systems is obvious. The basic reason is that human beings cannot survive in the absence of the organic life that supports them. Food production is a prime issue. But bioregenerative technologies also impact all the other ECLSS functions (atmosphere recycling, water treatment, etc.). Nevertheless, bioregenerative processes must be complemented with physico-chemical backup for redundancy reasons.

From the above, it is obvious that an engineering approach for MELiSSA development is mandatory. This includes a deep understanding of all parts of the unit operations (i.e. the compartments), and the processes have to be characterised by knowledge models and controlled by deterministic strategies. This clearly leads to focus on understanding, modelling and controlling the process.

The aim of the present paper was to give the state of the art concerning the development of the different compartments of the MELiSSA system, including the process demonstration and the assessment of control strategy efficiency.

Mathematical Modelling in the MELiSSA System

Mathematical Modelling of MELiSSA Overall System

An important aspect of the methodology adopted so far for MELiSSA engineering is the construction of mathematical models representing the behaviour of the subsystems (namely MELiSSA compartments and unit operations). The modelling of units operation, of compartments and of the complete loop is one of the original approaches of the MELiSSA project, in comparison to other international regenerative life support systems. This was chosen to build a reliable, robust and efficient regenerative LSS.

In general, the extremely detailed model is not really necessary. However, at the top level, two criteria have been retained for the validation of models for MELiSSA subsystems:

- robustness of the model, i.e. ability of the model to represent the behaviour of the system over a wide range of experimental conditions;
- mechanistic approach, i.e. deterministic approach by knowledge models taking into account the elementary phenomena instead of an empirical approach for building the mathematical description.

Of course, these two criteria are strictly linked together by the implicit assumption that if the model is deterministic and correct, its validity range is enlarged when compared to an empirical model and consequently allows scale-up and hardware modification. Applying these criteria to MELiSSA technology development is really a challenge, considering that the method must apply to microbial compartments in anoxigenic, aerobic or photosynthetic conditions and to higher plants chambers as well.

As presented in Fig. 2 [7], when applying these criteria to the MELiSSA compartments, this calls for a dual description of the processes, one which is related to physics and physico-chemistry the other one being concerned by the description of the physiology and metabolism. Therefore, the modelling challenges of the MELiSSA compartments and of the flow diagram of the entire loop can be summarised as follows:

- Deep understanding and mathematical representation of microorganism behaviours (and microbial communities or higher plant behaviours as well): This includes the description of the activity of the intracellular metabolism from the knowledge of the living cells environment; primarily, it includes a mandatory stoichiometry description (which is a clue for any closed system) coupled with kinetic modelling.
- Thorough understanding of physics and physico-chemistry of equilibrium properties of transport mechanisms, including the appraisal of the influence of non-terrestrial gravity conditions which represents a further degree of complexity;
- Fitting in the models of the different subsystems to achieve an overall representation of the global loop.

It is clear that such a challenge gives the direction and the frame of the long-term development of MELiSSA technologies. It is clearly related to basic research and development for MELiSSA. It must also be emphasised that none of these last three points are either completely new or in contradiction with the present developments of biotechnology and space technology, except the cross-intersection between challenges 1 and 2, which represents the modelling and the experimental investigation of the influence of space conditions on microbes or higher organisms metabolic activity.

Modelling of the Liquefying Compartment

The first compartment of MELiSSA is probably one of the most complex processes that have to perform the first treatment of all the solid and liquid wastes produced by the other compartments and principally the crew compartment, the higher plant chambers and the food preparation system [8]. A 100-l anaerobic bioreactor coupled with a membrane system has been developed ensuring at steady state the degradation of 70% of organic matter and solubilisation of 60% of

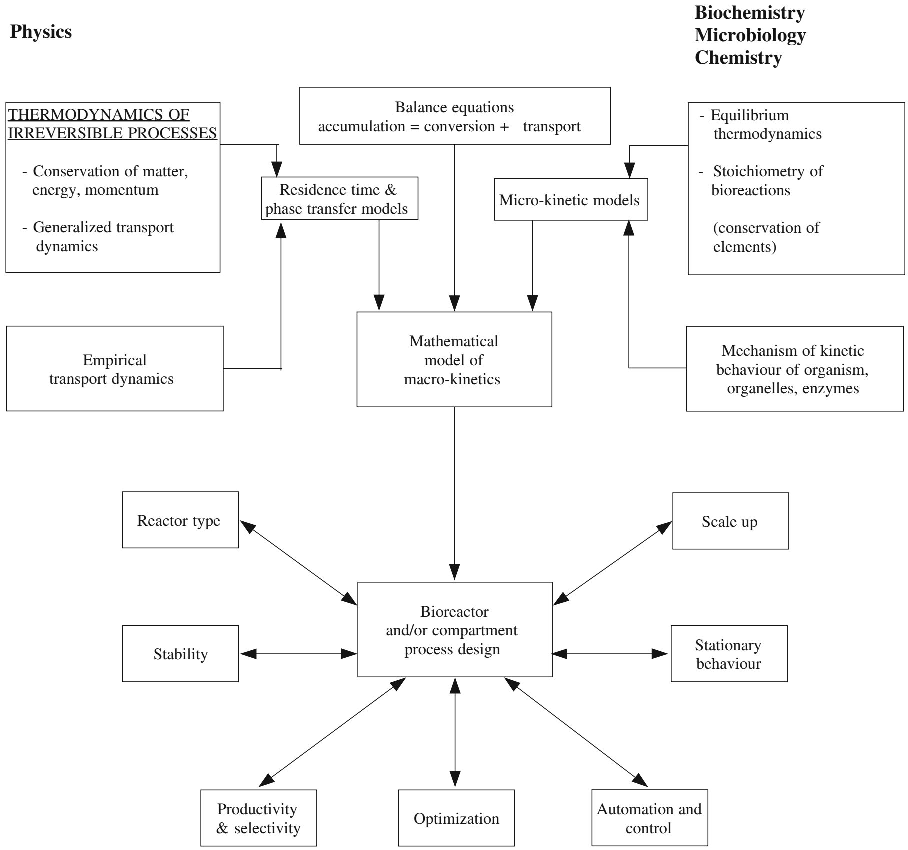

Fig. 2 The structure of (bio)chemical reaction engineering (from [7])

nitrogen. It is emphasised that the digester does not produce CH_4, which is an undesirable compound in the loop. Carbon is released only as CO_2 and volatile fatty acids. Nitrogen is released as ammonium. This is obtained by selecting a thermophilic consortium and by controlling the pH at a value which is lower than 6. The resulting global liquefying performances (several microbial consortia and conditions) are a degradation of 60–70% of the solid wastes.

An important challenge is the specific case of cellulolytic material which requires appropriate biological treatment. Thus, in parallel to the consortium of thermophilic bacteria, the degradation of plant wastes by *Fibrobacter succinogenes* has been investigated. An example of a culture of *F. succinogenes*, an anaerobic bacteria, is presented in Fig. 3 [9–10], showing the starting procedure during a 1,000-h experiment and the production of VFA associated with the degradation of vegetable wastes. Importantly, the degradation efficiencies are followed both by dry matter reduction and production of metabolites verifying that the elemental balances are satisfied. This is a clue for dealing with closed systems where the accumulation and/or the depletion of any element or product have to be strictly anticipated.

Modelling of the Photoheterotrophic Compartment

The photoheterotrophic compartment of MELiSSA is devoted to the transformation of volatile fatty acids evolved from the compartment I (anaerobic digester) into edible biomass

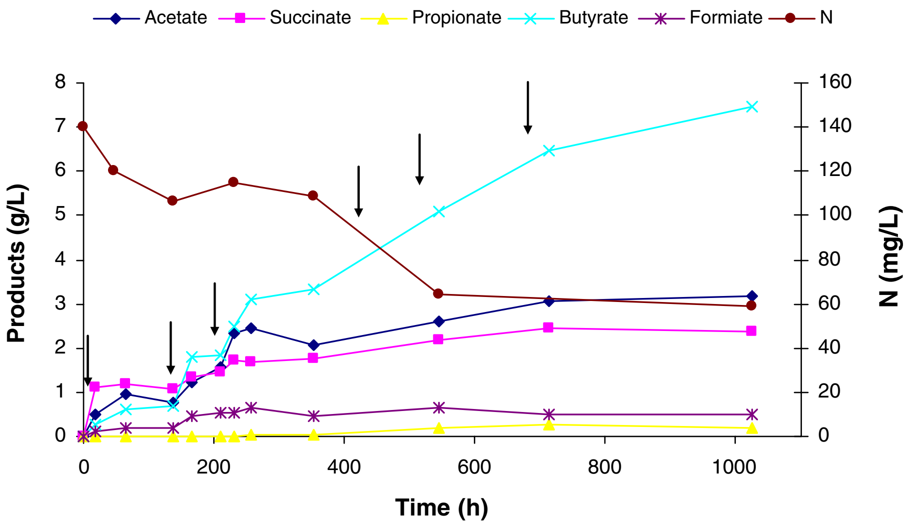

Fig. 3 Metabolites and nitrogen evolution during the degradation of a representative vegetable waste sample by *F. succinogenes*, an anaerobic rumen bacterium *Down arrow*: substrate addition

and CO_2. This step involves an anaerobic photoheterotrophic bioprocess corresponding to the *Rhodobacteriaceae* metabolism and particularly to the non-sulphur purple photosynthetic bacteria *Rs. rubrum* which has been chosen at the earlier stage of the MELiSSA loop design.

Experimental and modelling work has pointed out important stability problems leading to define an operative domain which relates incident radiant light flux, illuminated volume fraction and residence time in the photobioreactor.

The main important results [11–12] have demonstrated that continuous cultures of *Rs. rubrum* in photoheterotrophic conditions show a subcritical bifurcation for total biomass productivity, as reported in Fig. 4.

This means that a discontinuity in the reactor behaviour exists between a kinetic regime with low biomass productivity and a physically light-limited regime with a high productivity. These two regimes were observed and modelled from a critical value of the residence time and gave rise to a stable behaviour in all cases, except in the hysteresis loop (between the subcritical and critical values of the residence time) in which only the kinetic regime at low productivity was stable. This important feature regarding the performances of the PBR is probably linked to important metabolic changes in the coupling between the light radiant field and primarily photoheterotrophic kinetics events. It may also be linked in a lesser extent to complex hydrodynamics considerations in regard to the time constants involved in the alternate dark/light cycle for the cells. These results and analysis have led to propose the definition of operating conditions for engineering purposes in which it is possible to operate with the highest productivity (for a given incident light flux) between two values of critical residence time ranging roughly by a factor 3.

Modelling of the Nitrifying Compartment

The nitrifying compartment of MELiSSA is devoted to the transformation of ammonia produced by the compartment I (liquefying compartment) and not eliminated in compartment II. The function of the nitrifying compartment is to oxidise NH_4^+ into NO_3^- in order to provide to the following compartments a suitable source of nitrogen (mixture of NH_4^+/NO_3^- for the higher plants compartment and NO_3^- for the *Spirulina* compartment). It is colonised by two strains,

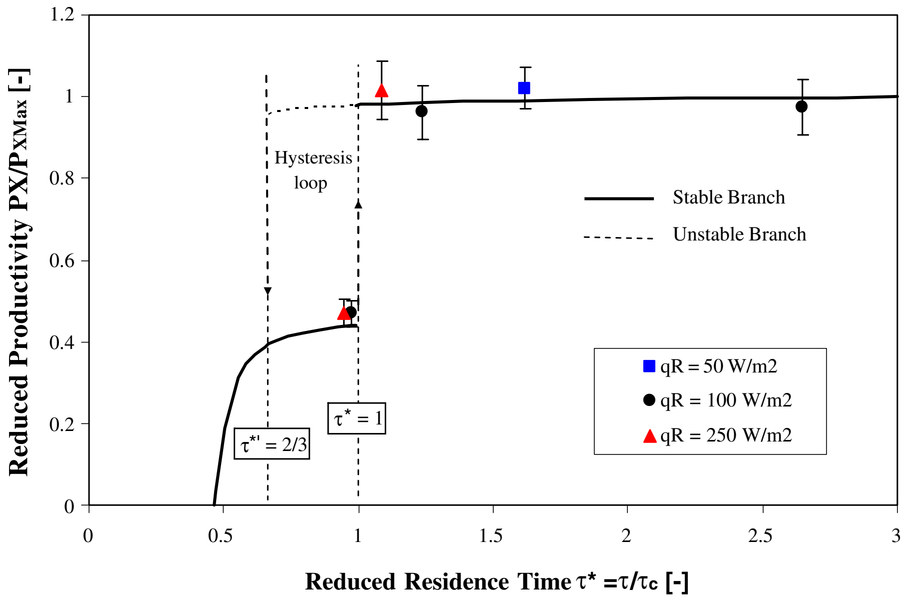

Fig. 4 Comparison between mathematical model and experimental data validating the subcritical bifurcation for total biomass productivity appearing at a given value of the residence time and displaying a hysteresis loop. Experimental data have been obtained on continuous cultures in PBR operating at different incident light fluxes q_R; the stable and unstable branches are also represented

Nitrosomonas europeae (conversion of NH_4^+ to NO_2^-) and *Nitrobacter winogradsky* (conversion NO_2^- to NO_3^-). This compartment is a fixed bed reactor, packed column with polystyrene beads, where biomass is fixed on the solid support with a slow growth and a conversion efficiency which is strictly dependent of oxygen transfer in the bed. Therefore, work has been focussed on two areas: the physical characterisation of the gas transfer capability (i.e. k_La measurement and correlation, residence time distributions of gas and liquid phases) and bench scale and pilot culture to obtain the kinetic characterisation of the growth and of ammonium oxidation [13].

Knowing that the complete behaviour of the reactor depends on many factors, the model elaborated for this reactor [14–17] enables to correctly account for biomass gradients, oxygen transfer rate, inhibition by substrates or products, oxido-reductive metabolism of the two strains, etc. (Fig. 5).

Modelling of the *Arthrospira platensis* Compartment

In terms of reactor productivity as well as in terms of controllability and response time, the microalgae compartments have proven to be more efficient than higher plant chambers. Algae and cyanobacteria (blue-green algae) are generally used as photosynthetic microorganisms to perform the carbon fixation in many experiments. These simple microorganisms are known to be genetically robust and capable of adapting to a wide range of culture conditions, including space flight conditions [18].

In MELiSSA, the blue-green algae *Arthrospira platensis* PCC 8005 (formerly called *Spirulina platensis* or *Spirulina*) is in charge of reprocessing carbon dioxide, nitrates and minerals produced by the other compartments into food and oxygen. Up to now, *Spirulina* cultures have been extensively studied at bench scale in laboratory experiments, and the main

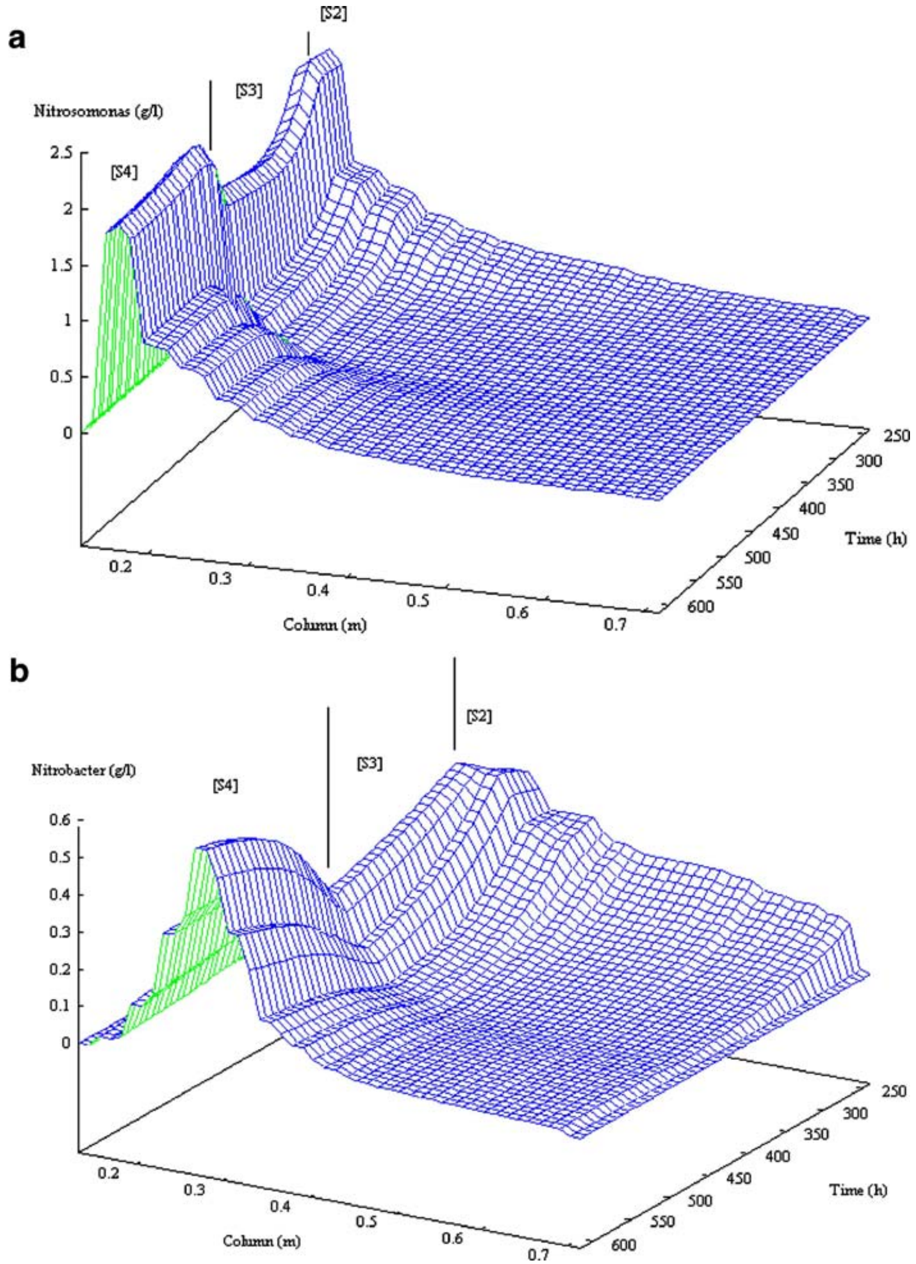

Fig. 5 Predictive modelling of *Nitrosomonas* (**a**) and *Nitrobacter* (**b**) profiles in fixed bed nitrifying columns

features of the metabolism of their growth under light energy transfer limitation have been thoroughly investigated [19–20]. Numerous previous investigations on *Arthrospira* sp. growth in submerged liquid media have demonstrated that the behaviour of the growth and the metabolic regulations are primarily controlled by the availability of light energy inside the reactor. Moreover, it has also been shown that light energy distribution inside the culture medium entails local growth rates and metabolic behaviour which have to be weighed through-out the entire culture volume to assess the overall growth kinetics. The consequence of such behaviour is that the growth is in practice limited during the entire culture by light energy flux inside the reactor volume with a more or less linear time course increase of biomass in the reactor, the slope of which is in a first approximation proportional to the incident light intensity and the specific illuminated area. However, it has been proven that such a strictly linear approximation is not sufficient for a suitable predictive control model of the compartment. A more complete model of radiant energy transfer in dense absorbing and diffusing media has been derived for *Arthrospira* sp. growth enabling to control biomass growth by light energy dissipation [21–24]. Furthermore, greater insight through sophisticated modelling of light energy conversion into chemical energy by photosynthetic microorganisms has enabled us to understand and predict the biomass composition as a function of light availability inside the photosynthetic compartments [25–26].

It must be noticed that this general modelling approach has been recently applied to other photosynthetic microorganisms in photobioreactors of different geometries operating in batch and continuous mode [27].

Modelling of the Higher Plants Compartment

Higher plant compartments are essential components of such a system for providing food, oxygen, fresh water and are a sink for carbon dioxide in parallel to the previous compartment. The technical challenge of integrating these compartments into an ecosystem must be met through exhaustive ground testing. Sensors are critical hardware components which require management algorithms, design criteria and calibration reliability. Minimum pressure and partial pressure requirements for sustaining plant life must be assessed with the concurrent influence on structural requirements.

In terms of modelling, the main difficulty is that plants are complex organisms. Consequently, it is difficult to develop suitable structured model for them. The plant growth modelling started in the MELiSSA project has led to experimental and theoretical investigations [28–29]. The main concluding remarks regarding the plants growth models have been summarised as follows:

- The dynamic growth models must provide expressions giving the carbon fixation rate by plants.
- The models have a form $\frac{dx}{dt} = f(t)$ rather than a form $\frac{dx}{dt} = f(t,x)$ as the classical microbial models. This means that the models are implicitly based on the repeatability of the growth over the time. This difference is important because it implicitly means that the growth rate is not proportional to the mass of the plant. Models are only dependent on environmental parameters (if the coefficients of the models take them into account) and time constants of the growth.
- The principles of the dynamic model for the plant growth are similar to the principles used for the growth of microorganisms: (1) the biological activity (including the growth) can be described by one or more mass balanced equations (stoichiometric approach); (2) to each stoichiometric equation is associated a reaction kinetics. This rate can be calculated using a specific dynamic model which enables to calculate the consumption/production rates of all the other compounds involved.

An attempt at establishing an exhaustive list of the growth parameters and of the variables involved in the growth of plants has been made. The main conclusion is that most of the environmental variables (temperature, pressure, humidity, etc.) would have to be controlled to obtain an optimal growth. This can be achieved only if plants are cultivated in controlled chambers. The growth itself can probably be controlled by light, CO_2 partial pressure and followed by the evolution of nutrients concentrations and CO_2 exhaustion. Among these parameters, light energy supply is easier to manage when artificial light is used.

There are already some reliable mathematical models for plant growth which have been implemented for the study of candidate crops for the MELiSSA loop. Some questions remain to be solved concerning their predictive behaviour, especially for variable daily conditions.

Development of a Model-Based Control Strategy

As stated before, one of the applications of mathematical modelling is the onset of the control strategy. Compared to their Earth counterpart, the drastic reduction in size of artificial LSS requires the replacement of the stochastic "natural" control by brain-level (intelligent) control. The intelligence of the control strategy is contained in the mathematical model which ought to contain the understanding of the system and is referred to as the knowledge model. More exactly, this will be the case if the command results from the optimisation of the evolution of the system which is simulated from its mathematical description, itself being issued from the thorough understanding of all the elementary steps or compartments.

It must also be emphasised that the time constants to manage in the MELiSSA system are very different and vary from less than 1 s at the metabolic level for the intimate regulation of microbial metabolism to less than 1 min for the exhaustion of the dissolved gas (O_2 in aerobic cultures), a few minutes for the removal or production gaseous O_2 or CO_2 in crew compartment or in higher plant chambers, several hours for the growth of microorganisms in submerged liquid cultures, several days for the liquefaction and digestion of solid wastes, several 10 weeks for the growth of higher plants, several months for the growth of microorganisms on solid supports or for altering the performances of membranes separation systems, etc. This calls for organising several layers of control (ranking from levels 0 to 3) which must be activated by different simplified models (derived models from a complete model) matching both physiological and physico-chemical descriptions.

Consequently, knowing the complexity of the MELiSSA system, partly because of the intrinsic connexity of matter flows diagram (Fig. 1) and partly because of the wide range of characteristic time constants, it becomes obvious that a generic system model approach has to be adopted (Fig. 6) to bring support during all the phases of the MELiSSA system life cycle for control purposes or management, tests, capitalisation and improvement purposes.

In practice, the knowledge model lies in the decision system part (Fig. 6). Depending on the kind of application, the process control may concern different hierarchical levels between the level close to the process and the level which manages the production.

The above fundamental rules for model-based engineering and control system perfectly apply to MELiSSA development. At the level of each compartment, the model (and the actual behaviour) are fundamentally complex and strongly nonlinear. The required level of control loops, based on simplified (reduced) models depending on the time horizon of the variables, must be determined. At the system level, by definition, MELiSSA is a loop with intricate recycling flows of matter and energy. This clearly calls for an overall control of the loop, knowing that the control of each unit operations cannot be installed without considering the system level objective.

Concluding Remarks

Up to now, large efforts have been devoted to the experimental study of each compartment of the MELiSSA system at bench and pilot scales. Compartments II, III and IV have been

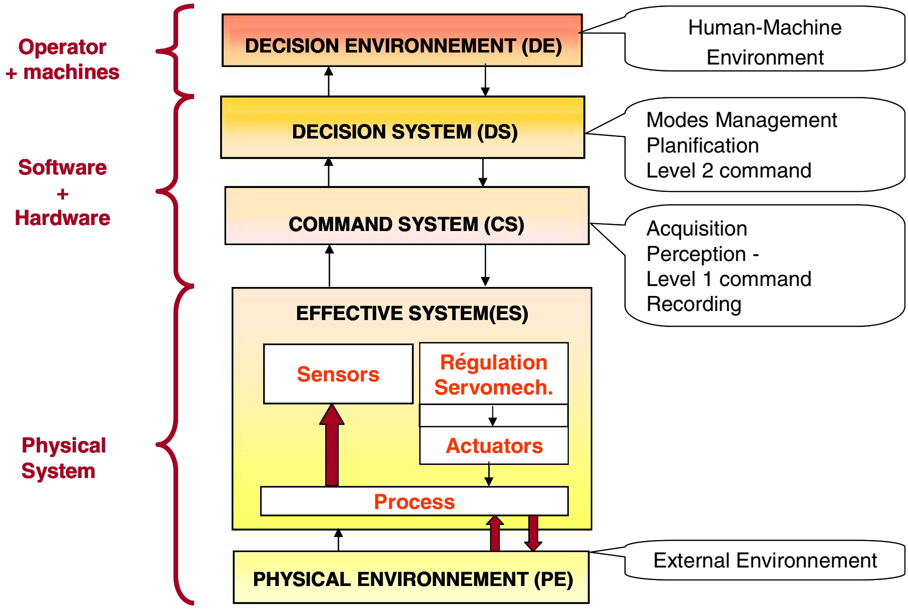

Fig. 6 General hierarchy between several definitions of model layers

experimentally interconnected [13, 30]. Regarding understanding and modelling of the behaviour of each compartment, the validation of the detailed models of each compartment is in progress at different degrees of development depending on the compartments. It has been proven by example for compartments II and IVa that a model-based control strategy is operative, showing that the deterministic control of a microbial process was possible and efficient provided the model is sufficiently robust. The six most abundant elements in the loop, C, H, N, O, P and S are correctly followed in a theoretical simulation at steady state of the entire loop.

However, further modelling investigation remains to be done at the level of each compartment to validate predictive dynamic models, including a wide range of non-steady-state experimental conditions. A deterministic control is a prerequisite of sustainable existence. This includes at the prime level, the triptych: (1) measurement by reliable sensors, (2) scheme of control and (3) regulation. This brain level of the manmade ecosystem is materialised by the mathematical deterministic modelling and simulation of the interacting parts of the system. This is related to the implicit assumption that if the model is deterministic and correct, its validity range is enlarged when compared to an empirical model. This is applied to the development of the technology of MELiSSA compartments, including microbial compartments but also the higher plants chambers, the crew compartment, the food preparation processes, etc. The MELiSSA experience of more than 15 years has shown that such an approach was:

- operative even when applied to subsystems containing living organisms such as microorganisms, microbial communities or higher plants provided the description, and the model contains metabolic understanding and transport phenomena.
- generic and capable of tackling with different loop configurations, including all kinds of unit operations (both physico-chemical and biological) and enabling comparisons in terms of recycling efficiencies.

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