CONTRIBUTIONS OF THE EDSTAR ENVIRONMENT AND INTEGRAL FORMULATION TO THE OPTIMAL DESIGN OF PHOTOBIOREACTORS WITH DILUTION OF RADIATIVE FLUX

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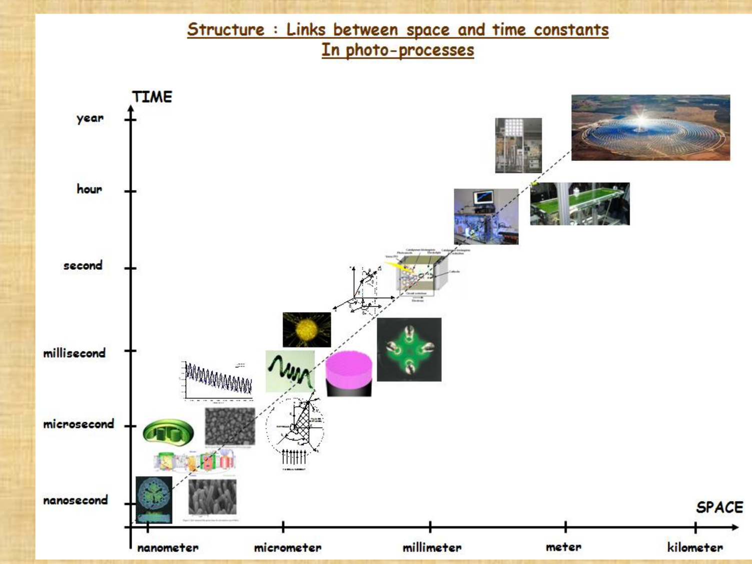
INTRODUCTION / CONTEXT

The conversion of solar energy to microalgal biomass in photobioreactors appears as a promising alternative to produce renewable chemicals with short time constant using biorefineries (biofuels, building block molecules, bioplastics, biomaterials, proteins for food and high valuable molecules). This requires to develop high efficiency photo-processes in order to minimize their footprint in the competition with other solar technologies producing mainly electricity. The photosynthesis efficiency being a given data of Nature, increasing the process efficiency is an engineering challenge only. An innovative approach consists in developing multi-scale knowledge models, the only way to ensure sufficient predictability and genericity for optimal design and advanced model based control of photobioreactors.

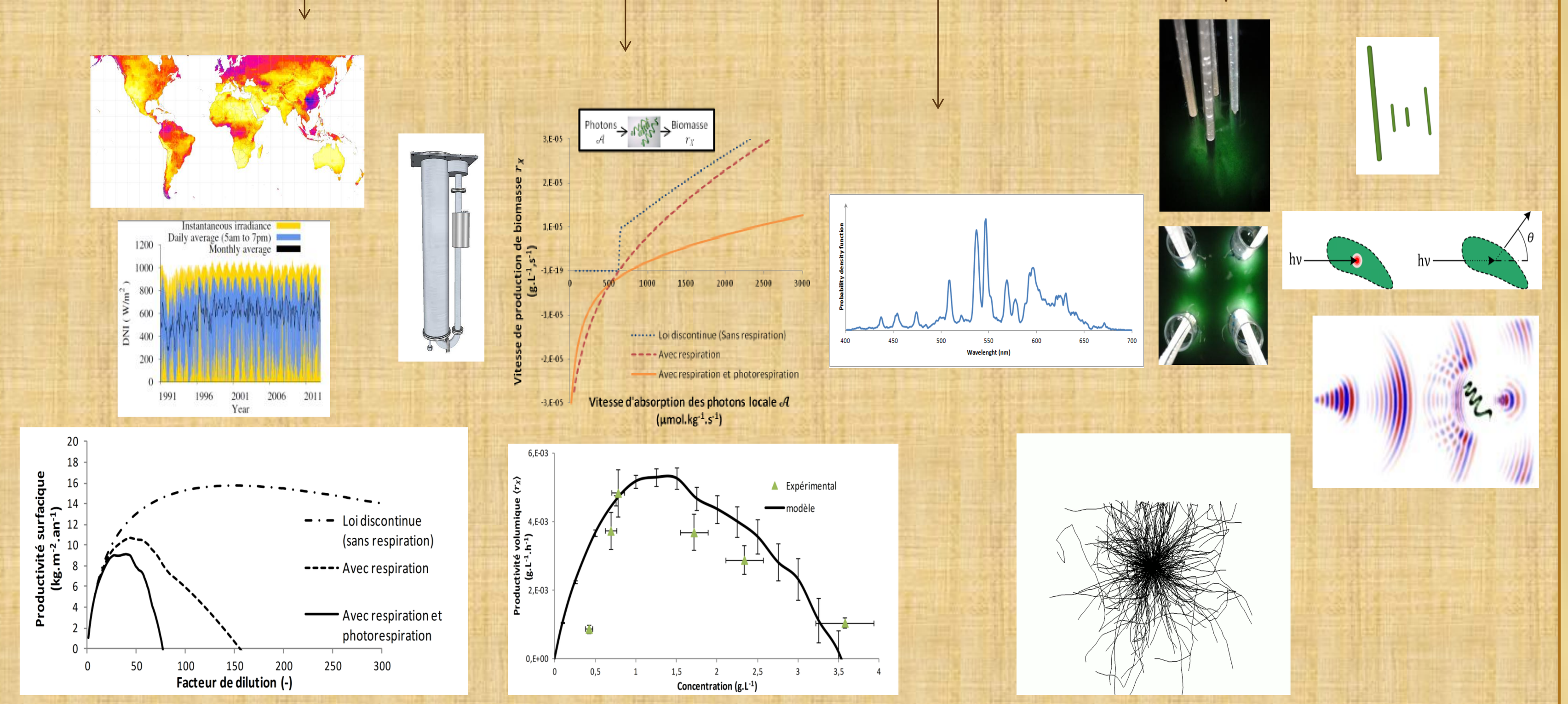
MULTISCALE KNOWLEDGE MODEL AND INTEGRAL FORMULATION



A multi-scale knowledge model describing all the controlling steps of the whole process has been developed. Its parameters have then been reified, i.e. their value were theoretically calculated (optical and radiative properties, quantum and energetic yields…) avoiding their identification on a specific sep-up and guarantying the genericity of the model that has been validated on hundreds of configurations and boundary conditions. The corresponding complexity at every space-time scales, including radiative transfer problems, is particularly well adapted to an integral formulation.

$$\int dt \int d\vec{r}\, \frac{1}{V}\, r_X \left(\int_{\lambda_{min}}^{\lambda_{max}} d\lambda\, p_\Lambda(\lambda) \int d\gamma\, p_\Gamma(\gamma)\, w(\gamma) \right)$$

year volume optical paths

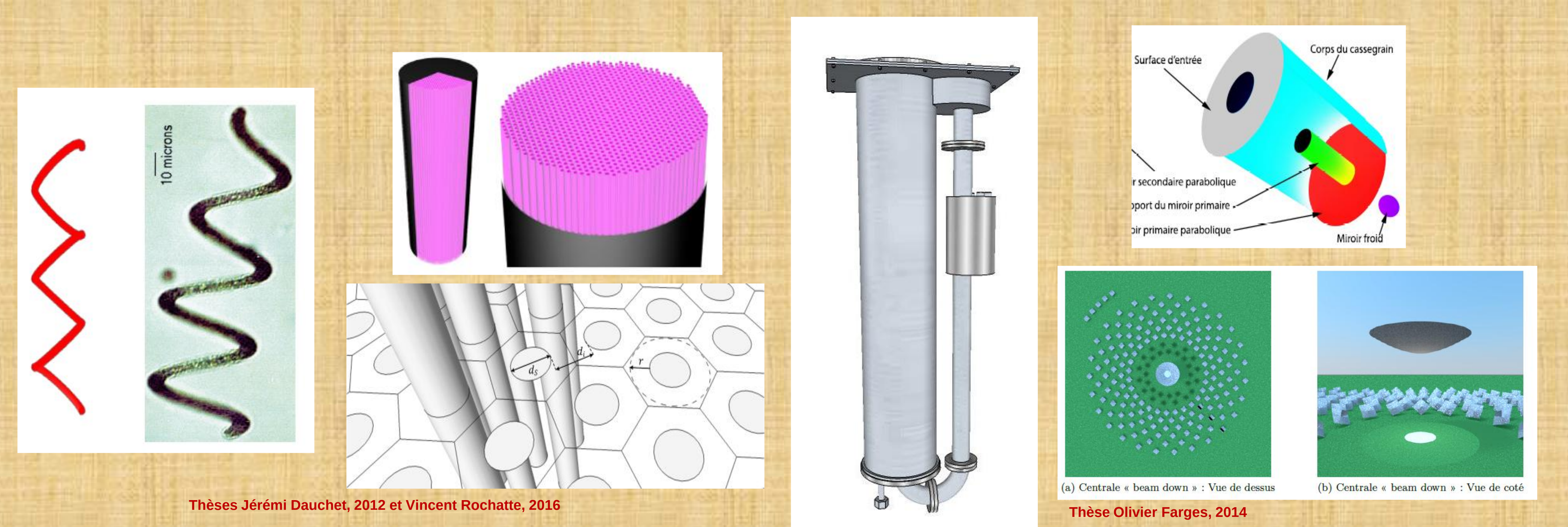


MONTE CARLO METHOD

The most recent advances in Monte Carlo method are used to solve the multi-scale and integral formulation knowledge model [1-5]. This method is usually considered as a reference for solving the radiative transfer equation, with systematic estimation of the standard error. Monte Carlo is also well-suited for solving high-dimensional integral problems generated by our multi-scale model. Furthermore, systematic sensitivity estimation to all the model parameters is available, with the same calculation time.

ORTHOGONALITY BETWEEN ALGORITHMS AND GEOMETRY IN THE EDSTAR ENVIRONMENT

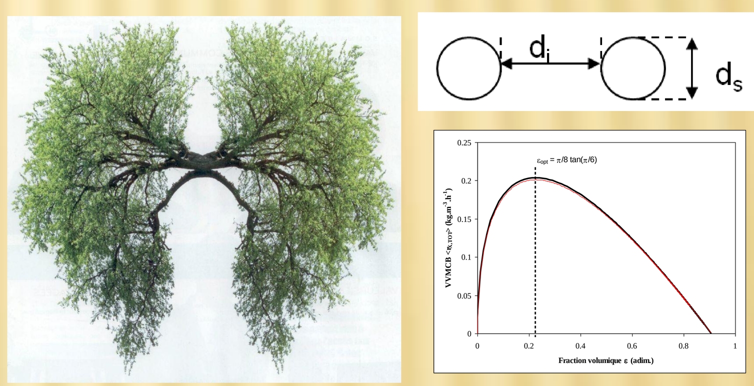
Numerical implementation is performed in EDStar, an open-source development environment that enables straightforward simulation of any geometry (directly provided by their CAD-file, see right panel), with the very same Monte Carlo algorithm. This orthogonality between geometric data and Monte Carlo sampling procedures perfectly meets the needs of engineering study: the algorithm is programmed without worrying of technical aspects that have no direct relation with physical reasoning (EDStar's scientific computation libraries handle statistical treatments, parallel implementation and pure geometrical reasoning) then the algorithm is validated in a simple geometry and finally it can be directly implemented within any complex geometry (without modifying the sampling procedure).



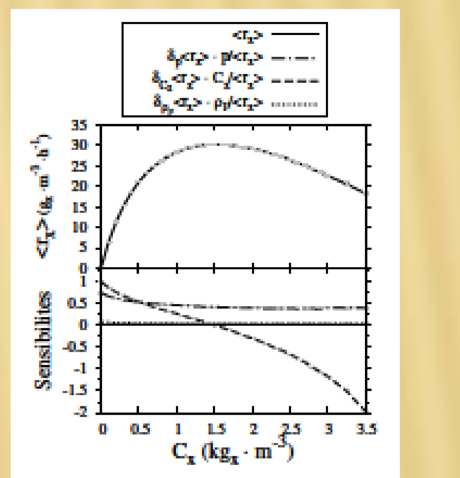
CAD-files illustrating the capabilities of the EDStar environment to manage multi-scale and geometric complexity

OPTIMIZATION PROCEDURE

The predictive knowledge models developed must be associated to any optimization approach in order to design highly thermodynamically efficient concepts of photobioreactors. To the date, the constructal approach has been used for a first 30L-prototype of photobioreactor [6]. It enables to minimize entropy generation at different scales of the process, associated with the corresponding optimal layout, leading step by step to the final design. Alternatively, an important breakthrough is expected regarding new capabilities of Monte Carlo method in calculating domain (geometry) sensitivities in the future. This method could authorize a direct calculation of the reactor optimal design (aggregating all the scales in an unique calculation) with lower calculation times under the constraint of maximizing energetic efficiency.



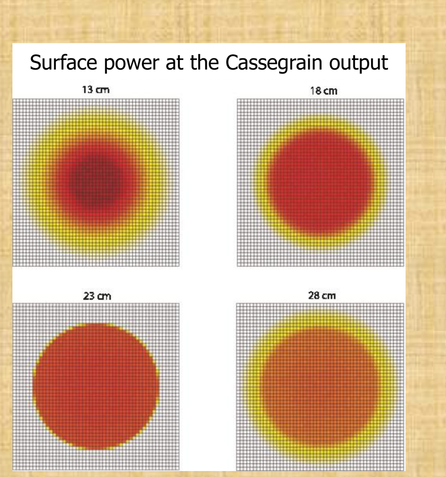
Constructal approach for multi-layout design optimization

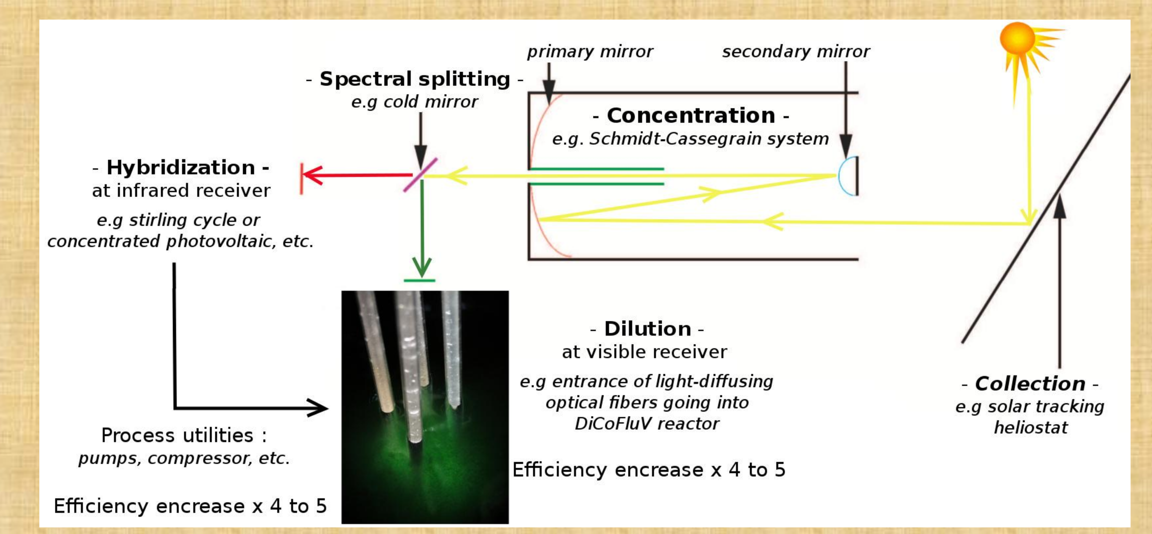


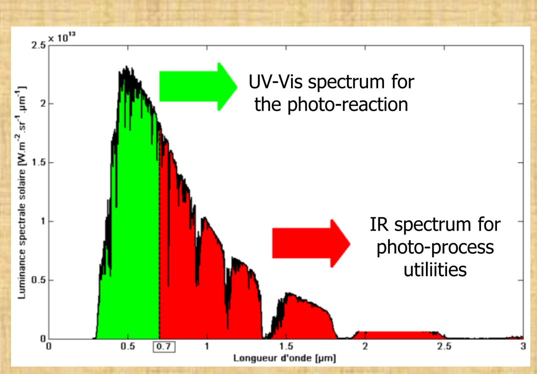
Sensitivity to the model parameter calculated by Monte Carlo method for design optimization

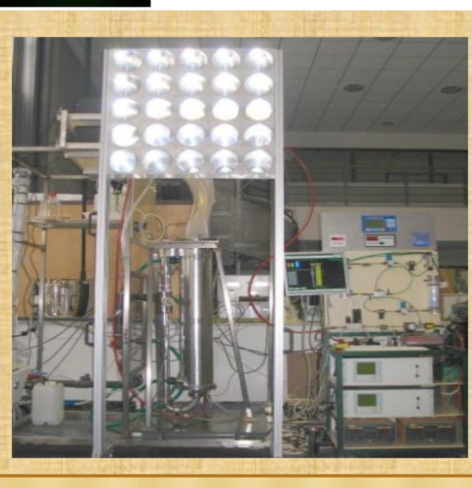
THE DILUTION – HYBRIDIZATION CONCEPT : PRINCIPLES

The sun full spectrum is collected by a surface far lower than the surface of illumination inside the photobioreactor using e.g. diffusing optical fibers (concept of light flux dilution DiCoFluV). After a concentration step, the UV-visible range of the spectrum is split to be used for photoreactions (biomass production) and the IR domain is converted by additional device operating under concentrated conditions in mechanical energy or electricity for the process utilities (hybridization concept). With such optimized technologies, industrial photobioreactors with 20% efficiency are expected in the future.

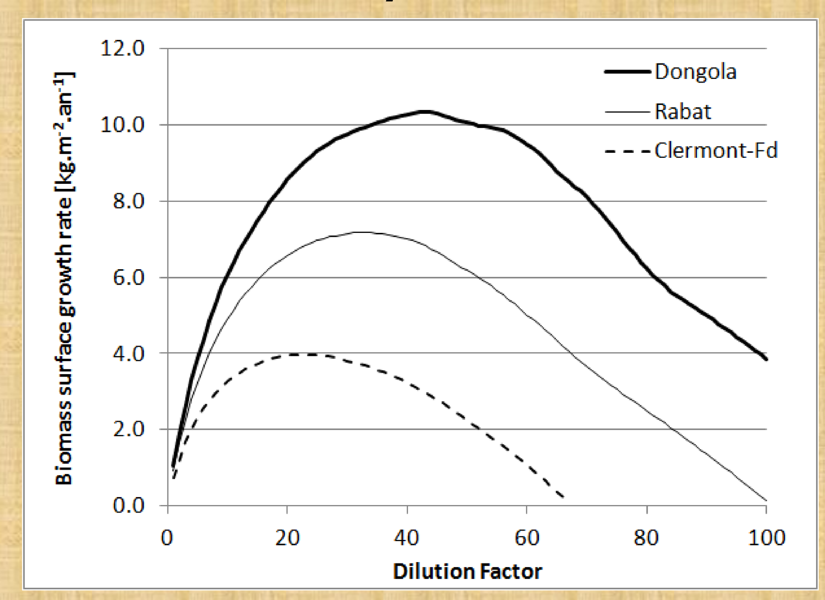








THE DILUTION – HYBRIDIZATION CONCEPT : RESULTS / PERSPECTIVES



Optimization procedure for the determination of the optimal dilution factor regarding earth location

-The dilution of incident solar flux enables to increase biomass surface growth rates by factors 4 to 6.

- The performance enhancement is higher in places with high yearly solar irradiation.

- As perspectives, an increase of the thermodynamic efficiency of the process by a factor 3 to 4 may be envisaged with the hybridization concept, without additional complicated or costly devices.

- Nevertheless, all these important developments require new general theoretical methods for multi-scale design optimization and improving technological efficiency of optics and materials for light transmission and conversion.

[1] Dauchet J., Blanco S., Cornet J.-F., Fournier R. 2015. *J. Quant. Spectrosc. Radiat. Transfer,* **161**: 60-84.
[2] Charon J., Blanco S., Cornet J.-F., Dauchet J., El Hafi M., Fournier R., Kaissar Abboud M., Weitz S. 2016. *J. Quant. Spectrosc. Radiat. Transfer,* **172**: 3-23.
[3] Dauchet J., Blanco S., Cornet J.-F., El Hafi M., Eymet V., Fournier R. 2013. *J. Quant. Spectrosc. Radiat. Transfer,* **128**: 52-59.
[4] Farges O., Bézian J. J., Bru H., El Hafi M., Fournier R., Spiesser C. 2015. *Solar Energy,* **113**: 57-62.
[5] Delatorre J. et al. 2014. *Solar Energy,* **103**: 653-681.
[6] Cornet J.-F. 2010. *Chem. Eng. Science,* **65**: 985-998.