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DEVELOPMENT OF A PHOTOBIOREACTOR FOR ACCELERATED MICROALGAE GROWTH USING THE INTEGRATED PRODUCT DESIGN METHODOLOGY

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Abstract. *The Microalgae cultivation in order to obtain biomass and biodiesel, presents itself as a promising solution due to the low amount of water used in the process and excellent productivity of microalgae for biodiesel extraction. In this context, the photobioreactor is an equipment used for biomass production in which the Microalgae has its growth accelerated. The development of a new photobioreactor configuration aims to achieve a higher efficiency system within a repeatable, allowing its use on industrial scale, thus differentiating it from existing equipments. To achieve this goal, it was used Integrated Product Development, worldwide known, where the main stages are: informational, concept, preliminary and detailed design. At first, patents and data about related products were sought and analyzed. Subsequently, the team generated concepts through CAD-Softwares and the most adequate model was chosen with methods according to the VDI 2221 process. After the concept selection, the relevant calculations and dimensioning were carried out through technical standards recommendations and FEM Analysis, resulting in the final product, followed by the B.O.M (Bill of Materials), assembly instructions, maintenance manual and the product's patent was created. After the detailed phase, the equipment was manufactured and tested, certifying the Design.*

Keywords: *Photobioreactor, Microalgae, Biomass, Product development.*

1. INTRODUCTION

The energy diversification of the non-renewable fuel matrix to renewable sources of energy is a worldwide discussed subject. Perhaps, it is the biggest political challenge of the last decades, since it involves many interests from several countries in the economic, social and environmental fields.

The damages caused by the non-renewable energy sources are increasingly being noticed by the mankind, leading to a high concern of the governments and the population about the subject. Because of that, people are trying to develop and use alternative sources of energy. According do the Renewable Energy Country Attractiveness (RECAI, 2014), during the year of 2014, almost 300 billions of dollars were invested in renewable energy around the world. Brazil is ranked in the 9th position in the RECAI world ranking, being one of the main Latin American countries to invest in alternative energy sources. If only the biomass is considered, the country climbs up to the 4th position in the ranking.

The biofuel production through microalgae proves itself as a promising alternative on the Green Fuels and sustainability fields. The algae cultivation basically exists in two forms: open systems (ponds and lakes) and closed systems (photobioreactors). The last one provides a full control of the environment, which allows a high crop productivity index. With the photobioreactor, it's possible to control the carbon dioxide, nutrients and water supply, in addition to suitable operating temperatures and sunlight exposure. Concerning the biodiesel productivity, the rates found in photobioreactors are about 5000 to 15000 gallons/hec.year, the highest productivity compared to the other sources: 100 to 300 times bigger compared to corn; 80 to 250 times bigger compared to the soybean oil; 55 to 160 times bigger compared to canola and 2 to 6 times compared to the productivity through castor beans (Zebib, 2008).

Other positive aspects of the biofuel production through microalgae in photobioreactors are: high sunlight use rates (due to an elevated Surface/Volume ratio), better protection against contaminations, space saving, etc. The main disadvantages encountered in photobioreactors are their complex geometry, productions costs still elevated and difficulties in some crop parameters. Thus, their total productivity levels and optimizations, which would confirm their place as the best alternative to biofuels production of our time, are still yet to be achieved.

In this way, the opportunity to develop a more efficient and cheaper model was presented to the design team. Through a partnership with the Balga Tecnologia Ambiental company and utilizing the Integrated Product Design Methodology (IDP), a new model was created. This methodology divides the product development in 4 distinct steps, in which specific design and engineering tools are applied to each one of them, thereby facilitating the process of innovation and product development.

2. OBJECTIVE

This paper presents each phase followed by the Integrated Product Design Methodology (IDP), applied to a flat plate photobioreactor for microalgae growth, which will be utilized for biomass and biofuel production. Regarding this matter, besides the traditional methodology and all its project phases (Informational, Conceptual, Preliminary and Detailed), several tools from the German methodology VDI2221 (VDI-Richtlinie 2221, 1993) were incorporated to the process in order to bring agility and quality to the project in the areas were the IDP lack of it. The result of this merging of the most suitable tools from each methodology was the development of these new photobioreactor in a very short time, meeting all the customer (Balga Tecnologia Ambiental) requirements and quality.

To achieve the proposed goal, the following activities took place:

1) Research of existing models; 2) Technological Prospection: a) Patents research on INPI , b) Patents research on Espacenet; 3) Project Specifications/Requirements; 4) Utility analysis matrix to evaluate the requirements weighting factors; 5) Function structure diagram for the product; 6) Sketches and 3D-Modelling of generated concepts; 7) Concepts evaluation (presentation for customer approval); 8) Materials selection; 9) Preliminary analysis and calculations;10) Standardization of selected tools; 11) Technical drawings; 12) Bill of materials and suppliers; 13) Gaskets sizing; 14) FEM Structural Analysis; 15) Final report and instruction manual.

3. PRODUCTION OF MICROALGAE FOR BIOMASS AND BIOFUEL

The search for an alternative fuel, capable of replacing the oil-based fuels is a major international effort, due to its non-renewable condition and the environmental pollution. Thus, the biodiesel production became an interesting alternative of renewable fuel source in comparison to the oil fuels. Nevertheless, there are some challenges to the full implementation of the biodiesel as the alternate fuel source, such as the incapacity to find sufficient raw material to supply the world fuel demand. Sugar cane, maize, soybean and palm are some of the currently sources, however they are also food crops, which may be harmful for the population. The UN (United Nations) express a strong disapproval in the use of food crops for biofuel production, due to its negative interference in food prices and shortage.

Another alternative is the production through microalgae, cellular organisms similar to plants, where the leaves grow through the capture of CO_2 from the atmosphere (also known as photosynthesis). During this process, the algae are multiplied, and can be converted into biomass, which can than be used for the production of biodiesel, fertilizers, pharmacists, pigments and many more. This process can be performed in opened photobioreactors (cheaper to build, operate and maintain, however it possess a low efficiency due to its low rate of sunlight utilization, external contamination, high evaporation rates and a low operational conditions control) or in closed photobioreactors (high productivity, low contamination risks and water consumption, high rate of sunlight utilization and good control of the operational conditions) (Oilgae, 2015). The negative aspects of closed photobioreactors are high complexity and production costs, besides the deterioration of materials.

Data from the Sustainable Energy Research Center, at the Utah State University (Zemke, *et al.*, 2014), shows that the efficiency of biodiesel production in an average photobioreactor are around 9%, due to lack of use from whole solar spectrum in photosynthesis (Infra-red and Ultraviolet radiations are not harnessed). Thus, an alternative to maximize the production rates are to increase the sunlight incidence during day and turbulence in the culture fluid during the process. This same research center concludes that cost for biofuel and energy production through microalgae are smaller than 1U$/kg.

It is important to remind that this evaluations of production rates were carried out in countries with lower intensity of solar rays compared to Brazil, being the Northeastern region of our country pointed as one of the best regions of the world for microalgae production, thanks to its solar intensity.

Due to its high sunlight intensity, Brazil is investing in energy production through photobioreactors, being the country to build the world's first large algae-based biofuel plant, with a capacity to produce 1,2 million liters of biodiesel per year, in the state of Pernambuco. The CO_2 capture source will be a sugar cane plantation, which is also used to ethanol production, thus performing a recycling process where the CO_2 rejected by the plantation would be the input to the photobioreactor process. Supplementary to the biofuel generation, production will attend food and pharmaceutical industries.

To produce fuel from solar energy, utilizing cellular organisms is a tempting idea. It is a "green technology" by its own nature, hence biofuel production (since the starch fermenting and cooking oil recycling till the algae conversion into aviation biofuel) collected more than US$ 126 billion in investments since 2003, according to the site of Bloomberg New Energy Finance (BNEF).

4. INTEGRATED PRODUCTS DEVELOPMENT APPLIED TO PHOTOBIOREACTOR

The main purposes of the product development methodologies are to facilitate and speed up the creation, concept elaboration and detailing of the developed product. The use of tested and approved methods has a high contribution to costs and time optimization on engineering projects, considering that design phase is most significant in the product's final cost (project phase corresponds to 5% on the cost accounting and influences about 70% of the project final cost, according to Smith & Reinertsen *apud* Forcellini, 2003).

In this way, many product development methodologies have been created worldwide, especially in engineering companies. To adapt to the new realities and market demands, such as launching time, cost reduction, better qualities requirements and higher complexity, these methodologies are still in constant improvement and revisions.

According to Forcellini (2003), the methodologies must show what to do, for whom, when, with what and how to do it. He states that "The project phase of a product includes activities ranging from the product specifications generation, through the development of working and appearance ideas, to the documentation and drawings elaboration, containing the information by which the product will be produced".

For Pahl & Beitz (2007), the planning and process of activities are divided in four main phases: Informational, Conceptual, Preliminary and Detailed. Through these phases it's possible to identify and evaluate required functions of product, elaborate solution principles, build modular structures and to execute complete final documentation of project.

The Integrated Product Design Methodology (IDP), adopted on the photobioreactor project will follow the project phases defined by Pahl & Beitz, with addition and adaptations from the German methodology VDI 2221. Henceforward, each phase and how they were applied on this project will be detailed.

4.1 Informational Design

The informational design is the first phase to be realized and its main purpose is to gather all the information and customer specifications about project, which will be the basis during development process. The informational design secondary objectives are: better understanding of existing problems and knowledge homogenization among members of the design team.

The main tools during the information design, focused on the photobioreactor design, were the client interview to gather all information of the product/process, the brainstorm and the categorization of requirements based on specific disciplines and topics. Based on those tools, it was possible to determine the client needs and the engineering requirements, which converts intangible needs into tangible requirements. The product customer interview, for instance, contributed for the development targeted to the client needs and expectations, collaborating with greater final product assertiveness. The brainstorming conducted by the project team and people linked to the subject allows better results for the creation and idea phase, because it potentially stimulates the creativity of all involved. Research articles, master and doctoral degree thesis help to understand how the development of this area and product are in Brazil and in the world, collaborating and closing the actors of this ecosystem. All these activities are carried out in order to obtain as much information as possible about the product, as well check whether the concept that customer wishes is really the best option in terms of engineering. The research of existing photobioreactors and technological prospection on INPI and Espacenet presented the several existing photobioreactor types and their models: opened or closed; tubular, bag, parallels plates and complex formats. Some relevant patents found in Brazil and worldwide were: PI1000925-6 A2, US6509188B1, US2010323436 e WO2005006838 A2. It is worth noting that this research allowed incorporating some accessories in order to increase the photobioreactor productivity as, for instance, the air lift (turbulence generator) and the optical fiber (increased brightness).

Figure 1. Examples of existing photobioreactors: Moss reactor, Foil and Plate

The type of photobioreactor to be developed (plate reactor) was defined by the customer. Furthermore, the following main needs were exposed: use of recyclable materials, transparent front panels, 10 centimeters space between the front plates, minimum height of 1 meter and maximum of 1,90 meters. Based on the data and applying the merging of the VDI 2221(German methodology which provides a better dynamism on the initial product development phases, through its tools, such as the utility analysis matrix, black box principle and many others) and IDP Methodologies best tools to generate the design requirements, the requirements of the project were determined: high area/volume ratio; flow vortices to improve the blending of particles; easy cleaning; high light capture efficiency; high energy efficiency; smallest water consumption as possible; low maintenance costs/number of parts; communicating vessels; inert and pH resistant; interchange between the light and dark phases of the photosynthesis and use of recyclable materials. This process defines the informational design ending.

4.2 Conceptual Design

The conceptual design is the second phase of the Integrated Product Development Methodology and has as purpose definition of a main concept for final product. To choose the most suitable concept, taking the customer and engineering requirements in consideration (defined on the last phase), several models were developed, aiming to show various existing possibilities.

The main tools used during conceptual design phase were: brainstorming, benchmarking, binary comparison (dominance matrix), black box method and utility analysis. The use of these tools improved the agility of the concept selection process and an appropriate evaluation of the requirement's weighting factors.

The first tool used was the Requirement's Paired Comparison, which assesses the correlation between the requirements. The correlations are: less important (value = 1), equally important (value = 2) or more important (value = 3). After matching all requirements among themselves, the values were added together, and the requirements ranked based on their weight. The eight most important requirements were, respectively: high energy efficiency; inert and pH resistant material; communicating vessels; low cost; flow vortices to improve the blending of particles; interchange between the light and dark phases of the photosynthesis; low maintenance cost; high area/volume ratio.

Subsequently, a Function Structure Diagram for the product was defined, which is a condensed and abstract statement which represents the ultimate product goal and its interfaces with other systems and the environment. Through this tool, it is possible to evaluate all the points involved in order to submit a complete solution. The tool used to define the global function (FSD) was the Black Box Method, in which the process inputs and outputs are indicated. This tool gives a better understanding of the product (its energy, material and information flow) and process, in this specific case, it helped to understand the resources and other features needed during the biomass production through photobioreactors.

Figure 2. Function Structure Diagram (FSD) by the Black Box Method

After the previous described steps, concepts were built into the product, always considering the customer needs and the project requirements. In order to improve the concept understanding and visualization, CAD software's are used to create the 3D models. Freehand drawings are also utilized in this phase, since new solutions are created during meetings and after the comparison of the 3D models. Some generated concepts are presented on Figure 3.

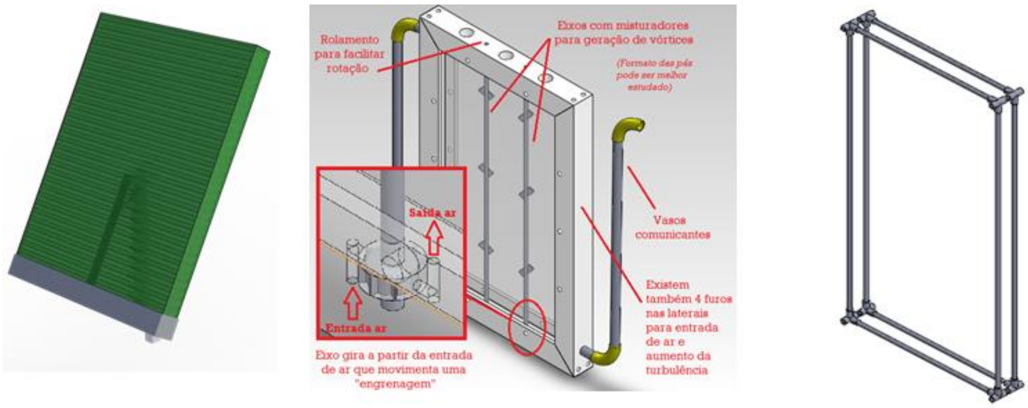

Figure 3. Concepts created

As the last step in the conceptual phase, concepts were discussed and Utility Analysis Tool applied, in order to evaluate each concept, according to the ranked Requirements and its weighting factors. For the classification of the best concept, each model receives a note for each requirement, values range from 0 to 4, where 0 = Failure, 1 = Passing, 2 = Satisfactory, 3 = Good, 4 = Excellent (full requirement fulfillment). These notes are then multiplied by the respective weight of each requirement. Finally, concept with the biggest note should be selected. For the photobioreactor design, some important considerations were made after the Utility Analysis Tool was utilized, such as: the control of the process temperature was not addressed during the design, therefore, its grades were low in almost all the concepts generated; energy efficiency had the same score for all concepts, since it is not possible to assess, at this stage of design, how much energy entered and left of the system to accomplish the calculation of energy efficiency; the communicating vessels and inert material requirements will exist for all concepts due to the client requirements, thus assigned same score for all generated concepts. These observations are relevant and explain to the customer why these requirements present such scores notes during the evaluation of concepts.In the photobioreactor project, one concept presented the largest final score note, however other models had bigger notes on more important requirements. Thus, after meeting with the customer, it was defined that the final concept would be a union of the best features of the best concepts. This final concept was modelled utilizing a CAD software, consequently ushering preliminary design phase.

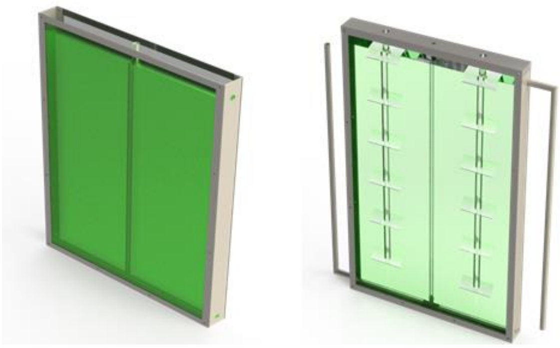

Figure 4. Final concept

4.3 Preliminary Design

The third phase of the Integrated Product Development Methodology is the preliminary design, which aims to define product dimensions, materials and further specifications based on the chosen concept during the conceptual design phase.

For this specific project, the following activities were performed: material selection; product structural preliminary analysis; machine elements calculations; search for standardized parts; and verification of easy equipment assembly and maintenance alternatives.

As in previous phases, the preliminary design uses specific tools throughout its development. The main tools used were related to final product concept 3D modeling, analytical calculations and preliminary structural analysis (rule-based), being held in engineering software and based on technical norms.

The materials selection took into consideration that product would not be exposed to extreme conditions, thus its most important properties were related to the mechanical strength, being performed a FEM structural analysis to evaluate and certify loading conditions. To perform this selection, once more the project's requirements defined in the conceptual design were assessed, utilizing technical handbooks and bibliographies about materials such as Callister (2002) .Furthermore the mechanical strength, other features were also considered, such as: material wear, temperature resistance and process conditions, shapes available in the market, among others. Some important considerations of this activity: material properties extracted from tables of vendors; small production scale; non-use of metallic material (customer requirement); contact with companies for price evaluation.

Thus, after considering some options, the following materials have been defined for each component: polyethylene (cover; lid; side frame right, left and bottom), TEADIT NA 1002 (attachment between membrane and body), PVC (pipes, pipe fittings and air-lift), PMMA (membrane), optical fibber.

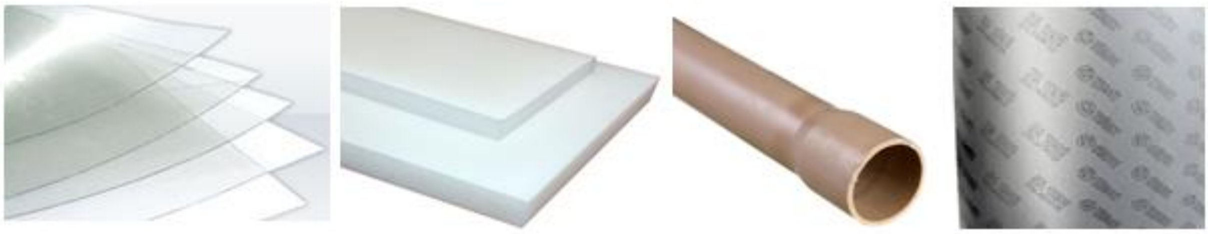

Figure 5. Examples of materials: PMMA (Acrylic), polyethylene, pipes (PVC), TEADIT union.

The bolts have been sized based on technical standards. The adopted reference was the book “Industrial Gaskets” wrote by José Carlos Veiga, Third Edition (2003). One of main parameters of project was correct torque specification on the bolts, due to its key role in holding all hydrostatic pressure on membrane and keeping correct sealing on the gaskets. For this sizing, an industrial condition was considered, where it is recommended by standards, that a condition of helium leakage between 10^{-4} and 10^{-8} cm³/s or inferior represents a no leaking situation. Due to the similarity between the photobioreactor configuration and an industrial pipe flange, it was considered that both cases had the same forces configurations, which is described in Figure 6.

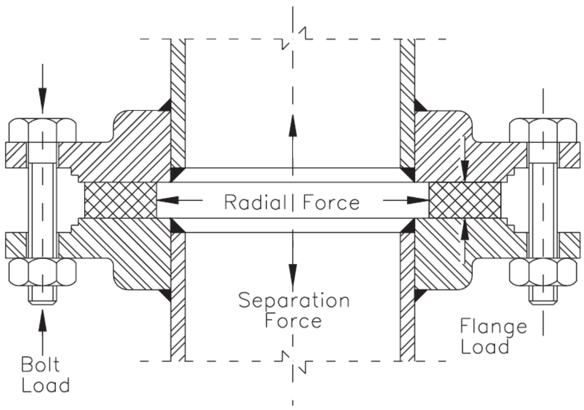

Figure 6. Force Schematic in an industrial gasket

The Appendices 2 from Section VIII of ASME (2011) requires that an industrial gasket is calculated by two methods independently and after those calculations, the results should be compared and the more critical should be selected. The methods are: operation pressure and minimum operation tension.

Moreover it is extremely necessary to determine the optimum torque needed to guarantee that there is no presence of leakage. According to the recommendations, the torque was calculated as below (the highest result was then used to tighten the bolts):

$$T_1 = (k \cdot W_{m1} \cdot d) / N_p \quad (1)$$

$$T_2 = (k \cdot W_{m2} \cdot d) / N_p \quad (2)$$

Where: T_1 and T_2 = Torque calculated; k = Grip factor; W_{m1} = Minimum strength of the screws (through the operation pressure); W_{m2} = Minimum strength of the screws (through the minimum stress and without considering fluid pressure); d = Nominal diameter; N_p = Number of screws.

The structural analyses were performed utilizing the Finite Elements Method (FEM), through proper engineering software. The main objectives of the analyses were the components dimensioning and further improvement, through the evaluation of the smallest thickness possible to be used in order to reduce costs and weight of the product. The material properties considered were obtained with suppliers and checked on matweb.com (Acrylic (PMMA): Modulus of Elasticity: 3,24 GPa and Poisson's ratio = 0,4). The following considerations were admitted: input dimensions in millimeters, lower base fixed on the floor (boundary condition), load applied on four different sections of the membrane for to best represent hydrostatic pressure variation at different heights (Pressure 1 = 0,014 N/mm²; Pressure 2 = 0,0105 N/mm²; Pressure 3 = 0,007 N/mm²; Pressure 4 = 0,0035 N/mm²).

In the analyses, plate of 8 mm of acrylic (PMMA) was considered. Three different configurations were evaluated (without and with bracings on horizontal and vertical directions). For the 8 mm plate of PMMA, the maximum displacement of 11,1 cm was found (on top of the membrane), and the maximum tension of 30,8 MPa was encountered (with bracings on vertical direction). The values found are within the safe zone admitted to the material. Additionally, the use of three horizontal bracings, in order to reduce the strain at the top was predefined. Thus, the deformation and maximum stress found will not cause any problems to the equipment, ensuring its correct operation.

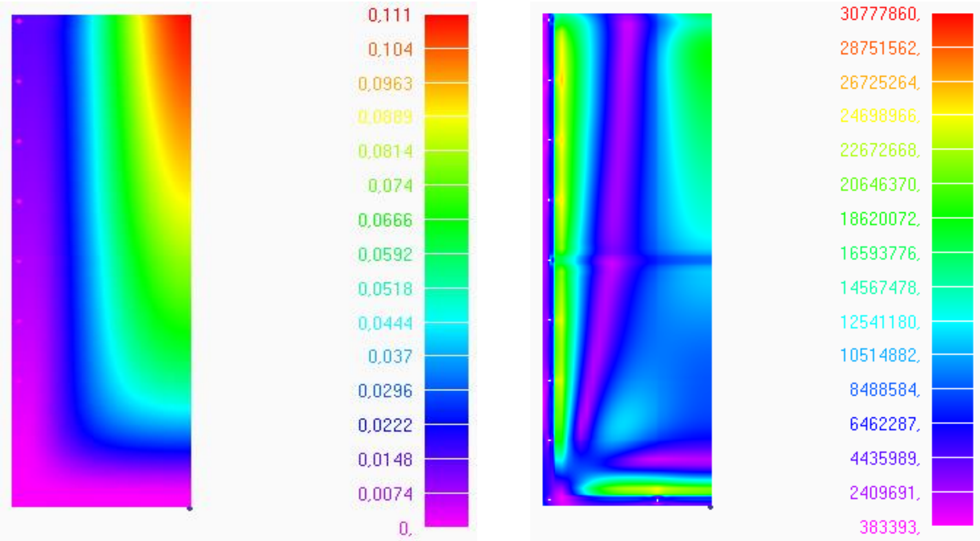

Figure 7. Maximum displacement and maximum tension for 8 mm plate PMMA

4.4 Detailed Design

The last phase of the Integrated Product Development Methodology is the detailed design, which has as objective to enclose all design, exposing all needed information to manufacture the prototype and test it.

On the photobioreactor design all technical drawing from each part of the equipment were generated due to the manufacturing, also the bill of material and suppliers were informed due to facilitate the client work on purchasing them; as well the report and technical manuals were delivered.

Unlike other design phases (informational, conceptual and preliminary), in the detailed design, there are no specific tools to be applied. Technical drawings are generated from the CAE models performed in the preliminary phase and the bill of materials and suppliers is elaborated from market research.

Overall, the detailed design encloses the Integrated Product Development Methodology, including all needed data to manufacture the prototype and test it.

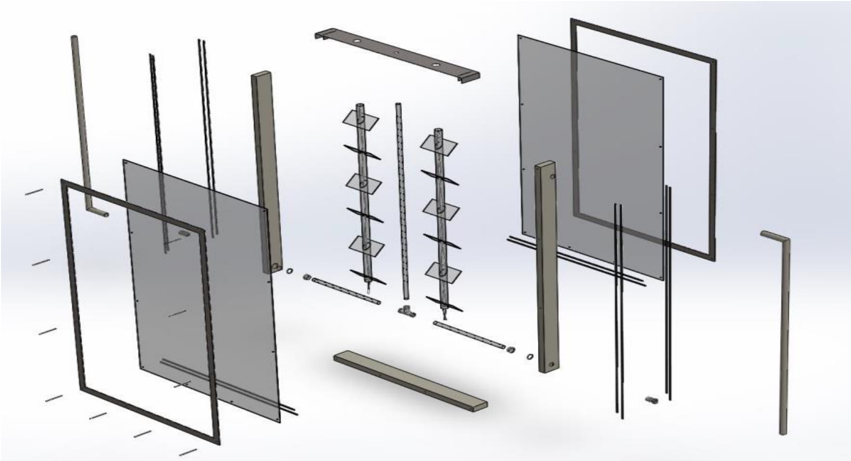

Figure 8. Exploded view of photobioreactor

5. ACKNOWLEDGEMENTS

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