Optimization of light intensity in a controlled ecological life support system based on a knowledge- and data-driven modeling approach

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***Abstract*—A Controlled Ecological Life Support System (CELSS) is necessary for the long-term manned space exploration. A primary goal of plant research for CELSS is to generate the largest amount of edible biomass possible for the least amount of electrical energy used. A key factor for implementing crop production systems will be the development of energy-efficient lighting approaches. Artificial lighting is essential in plant production in a CELSS, and energy reduction is one of the most important problems to be solved. The objective of this study is to provide a scheme of light intensity control in order to determine the most suitable light intensity in CELSS for plant cultivation, which can minimum the energy consumption and meet the demand of plant production and oxygen for the crew based on a knowledge-and data-driven modeling approach. The results indicate that the optimization method can increase 11.5% light use efficiency compared to the previous experimental set. Moreover, the biomass production increases under the optimized light intensity. This approach provides a computational basis for life-time optimization of cabin design and experimental setup of CELSS.**

Keywords—Optimization; knowledge-and data-driven modeling; CELSS; Light intensity; Energy consumption

I. INTRODUCTION

A Controlled Ecological Life Support System (CELSS) is necessary for the long-term manned space exploration, extraterrestrial living and space technology development [1]. A plant production module is one of the modules comprising a CELSS, and it is expected to play an important role in the system [2]. The use of higher plants for food production has been proposed for long duration or large scale manned space missions to minimize the prohibitively large storage and resupply costs [3]. Plants (crops) could serve a vital role for these regenerative life support systems, where photosynthesis is used to provide oxygen and food while removing waste carbon dioxide and recycles waste water [4, 5]. As mission distances and durations increase, the role for plants could expand, where crops are then used for most of the atmospheric regeneration and provide major portions of carbohydrate, protein and oil for the crew [4].

The downside is that such a bioregenerative life-support system must be highly complex and relatively massive to maintain a proper composition of the atmosphere while also providing food [6]. A primary goal of plant research for CELSS is to generate the largest amount of edible biomass possible for the least amount of electrical energy used (i.e., optimize for energy-use efficiency) [7].

CELSS research had been started in America and Russia before a manned space flight was launched in 1950s, and 1-4 person and 3-180 days CELSS integration experiments that achieved partial closed circulation were processed in succession in 1970s-1980s [8, 9]. A 2-person 30-day CELSS integration experiment was processed in a CELSS integration experiment platform to research the trait of air and water exchanging and the dynamic balance regulating technology in order to establish a basis for a larger scale integrated test in China [1, 10]. Amount of researches on the simulation and control of plant growth in greenhouse have been performed [11-13]. However, for plant production in a CELSS, the gas and light environments are very different compared to those in greenhouse [14]. A key factor for implementing crop production systems will be the development of energy-efficient lighting approaches.

As the environments are completely artificial and controllable in a space CELSS, artificial lighting is essential in plant production in a CELSS, and energy reduction is one of the most important problems to be solved [14]. Precise control of environmental conditions will be necessary to obtain maximal crop yields within a regenerative life support system. A few studies have demonstrated that plant growth is most rapid with continuous light of moderately high intensity (greater that 300 uE m^{-2} sec^{-1}) [15]. Moreover, plant photosynthetic rate and yield increase with the increase of light intensity, but the amplification will decrease gradually. The yield will no longer increase with the light intensity when it reaches some value, while the light use efficiency will decrease with the increase of light intensity [16]. As a prerequisite, to

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ensure the demands of crew for the food and oxygen, to select the level of light intensity can improve the energy use efficiency of CELSS. As light is the energy source of plants and the major parts of energy consumption, the selection of light source and the control of light intensity play an important role for improving the use efficiency of energy [16].

LED lights are the preferred light source for the cultivation of plants in a controlled environment due to their superior performance [17]. Although the advancements in LED technology increased the efficiency of plant illumination in recent years and it will increase even more in the following years, plant cultivation has high energy demands. While past plant growth chambers typically required only a few hundred Watt, because of their limited size, future food production greenhouses in space will need a substantial part of the total energy budget of a spacecraft or planetary base. Means to reduce the energy demand are therefore a high priority for future plant cultivation technology development [18]. On the one hand, small light intensity cannot meet the optimum growth requirements of the plant and the oxygen demand of the crew in the cabin; on the other hand, large light intensity will lead to high energy consumption of the closed system.

The objective of this study is to provide a scheme of light intensity control in order to determine the most suitable light intensity in CELSS for plant cultivation, which can minimize the energy consumption and meet the demand of plant production and oxygen for the crew based on a knowledge-and data-driven modeling approach.

II. MATERIALS AND METHODS

A. Model Description

1) Knowledge-and-Data-Driven Model (KDDM)

A knowledge-and-data-driven model (KDDM) can be used for simulating both plant growth and the dynamics of CO_2/O_2 in a closed ecological life support system of plant and human being [19]. It consists of the 'knowledge-driven (KD)' submodel and the 'data-driven (DD)' submodel, as schematically shown in Fig.1. The material flow of the system is shown in Fig. 2.

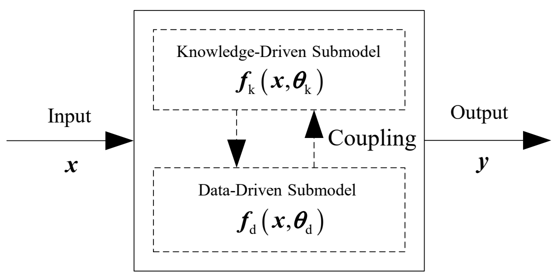

Fig. 1. Schematic diagram of the knowledge-and-data-driven model (KDDM), which primarily consists of the 'knowledge-driven (KD)' submodel and 'data-driven (DD)' submodel [20].

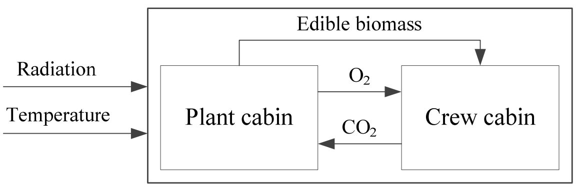

Fig. 2. Material flow of the system (modified from Fig. 2 in Guo et al. [10]).

In this work, the GreenLab+ for biomass production and its partitioning was adopted as the KD submodel and the piecewise linear model (PLM) for CO_2 production and O_2 consumption by the crew as the DD submodel. The two submodels were integrated through the mass balance model (MBM) with metabolic stoichiometries, which was derived for CO_2/O_2 concentration in a closed system of plant and crew. Here, only the basic features or equations of the model were outlined and a more detailed model description can be found in [19, 20].

a) Knowledge-Driven Model (GreenLab+)

GreenLab+ can simulate the plant process recursively with the principle of source-sink equilibrium, and compute the biomass production linked to the external conditions (i.e., light, temperature, CO_2). The principles of the GreenLab+ are shown in Fig.3. The time step used for calculating crop photosynthesis and maintenance respiration is 1 minute. Summing up these data gives the daily dry matter production. Biomass allocation and organ expansion is computed daily, with an implicit assumption that plant morphology is stable during one day.

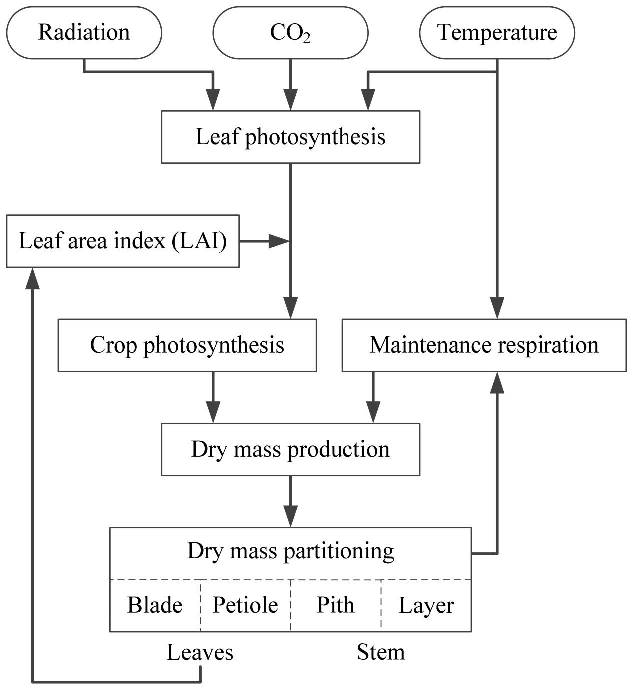

Fig. 3. The framework of GreenLab+.

In GreenLab+, daily dry matter (DM) production, *dW/dt*, is calculated as in (1):

$$\frac{dW}{dt} = C_f \cdot (P_{gd} - R_m) \qquad (1)$$

Where dW/dt is the crop growth rate (g DM m^{-2} d^{-1}); C_f is the conversion efficiency from assimilates to dry matter (g DM g^{-1} CH_2O); P_{gd} is the daily crop gross assimilation rate per unit ground area (g CH_2O m^{-2} d^{-1}); and R_m is the daily maintenance respiration rate per unit ground area (g CH_2O m^{-2} d^{-1}).

The daily crop gross assimilation rate, P_{gd}, is calculated by integrating the instantaneous leaf assimilation rates (P_{gc}, μmol CO_2 m^{-2} s^{-1}) along the canopy depth, as in (2). Instantaneous assimilation rates at a given canopy depth is computed using a negative exponential light-response curve, see (3). The light intensity decreases exponentially with leaf area index within the canopy, see 4.

$$P_{\mathrm{gd}} = \int_{T_1}^{T_2} \int_{0}^{\mathrm{LAI}} P_{\mathrm{gc}}\, \mathrm{d}L\, \mathrm{d}t \tag{2}$$

$$P_{\mathrm{gc}} = P_{\mathrm{gc,max}} \left[1 - \exp\left(-\varepsilon \cdot \frac{I}{P_{\mathrm{gc,max}}} \right) \right] \tag{3}$$

$$I = kI_0 e^{-kL} \tag{4}$$

In (2), T_1 and T_2 are the beginning and end time of measuring a day, chosen as 09:00 h each day; LAI is the leaf area index of canopy (m^2 m^{-2}); L is the canopy depth, valued as from zero (canopy top) to LAI (canopy bottom). In (3), I is the photosynthetic photon flux density (μmol m^{-2} s^{-1}), ε is the photochemical efficiency (mol CO_2 mol^{-1} photon absorbed), and $P_{gc,max}$ is the leaf photosynthetic rate at light saturation (μmol CO_2 m^{-2} s^{-1}). Note that $P_{gc,max}$ is a function of several environmental variables, primarily temperature, CO_2 concentration in the atmosphere of the cabin, not all of which are explicitly given in (3). In (4), k is the light extinction coefficient; I_0 is the incoming photon flux intensity at the top of the plant canopy (μmol photon m^{-2} s^{-1}), which is an unknown input variable to be optimized in this work.

b) Data-Driven Model (PLM)

Each person in the crew cabin strictly follows the same work and rest regime every day during the 2-person-30-day CELSS integrated test, so that their activities may be divided into 4 types according to levels of strength (Table 1).

Therefore, a piecewise linear model (PLM) was used for simulating CO_2 production and O_2 consumption by the crew, as in (5) and (6):

$$K_{\mathrm{CO_2}} = \sum_{i=\mathrm{S,W,M,P}} n_i \kappa_{\mathrm{CO_2},i} \tag{5}$$

$$K_{\mathrm{O_2}} = \sum_{i=\mathrm{S,W,M,P}} n_i \kappa_{\mathrm{O_2},i} \tag{6}$$

where $K_{\mathrm{CO_2}}$ and $K_{\mathrm{O_2}}$ are the daily CO_2 production and O_2 consumption rates per person, respectively; i is a type label for different levels of activities (Sleeping, S; Normal working, W; Morning exercises, M; Physical exercises, P); n_i is the number of hours for the type label i (Table 1); and $\kappa_{\mathrm{CO_2},i}$ and $\kappa_{\mathrm{O_2},i}$ are the hourly CO_2 production and O_2 consumption rates of the type label i per person, respectively (g h^{-1} $person^{-1}$).

TABLE I. WORK AND REST REGIMES OF THE CREW WITHIN 24 HOURS PER DAY FOR DIFFERENT LEVELS OF ACTIVITIES.

Types	Levels of activity	Activity	Interval[a]	Num. of hours	CO_2 production rate (g h^{-1} person-1)	O_2 consumption rate (g h^{-1} $person^{-1}$)
1	Low level of activity	Sleeping (S)	13-15, 22-24, 0-5	9	38.9	28.3
2	Light activity	Normal working (W)	8-12, 15-22	11	47.4	37.5
3	Moderate activity	Morning exercises (M)	5-8	3	71.4	52.0
4	Heavy activity	Physical exercises (P)	12-13	1	81.0	58.9

a. Indicated by hours during a day, from 0 to 24.

c) Mass Balance Model (MBM)

Photosynthesis and respiration reactions affect the production of biomass, as well as the exchange of CO_2/O_2 concentration between plant and atmosphere. According to the reaction scheme ($\mathrm{CO_2 + H_2O \overset{light}{\Longleftrightarrow} CH_2O + O_2}$), the mass balance model (MBM) of the reactions was used for CO_2/O_2 concentration in a closed system of plant and crew, as in (7) and (8):

$$\frac{\mathrm{d}C_a}{\mathrm{d}t} = \frac{-\frac{44}{30}(P_{\mathrm{gd}} - R_{\mathrm{m}})\mathrm{S_{plant}} + \lambda K_{\mathrm{CO_2}}}{V_{\mathrm{CITP}}} \tag{7}$$

$$\frac{\mathrm{d}O_a}{\mathrm{d}t} = \frac{\frac{32}{30}(P_{\mathrm{gd}} - R_{\mathrm{m}})\mathrm{S_{plant}} - \lambda K_{\mathrm{O_2}}}{V_{\mathrm{CITP}}} \tag{8}$$

where C_a and O_a are the CO_2 and O_2 concentrations in the atmosphere of the cabin, respectively (g m^{-3}); V_{CITP} is the volume of CITP, set to 308 m^3; S_{plant} is the cultivation area of the plant, set to 36 m^2; 44/30 and 32/30 are the conversion coefficients from carbohydrate formulated as CH_2O to CO_2 and O_2, respectively, the numerical values representing the molecular weights of CO_2, CH_2O and O_2, respectively; λ is the number of crew in the cabin, set to 2; $K_{\mathrm{CO_2}}$ and $K_{\mathrm{O_2}}$ are the daily CO_2 production and O_2 consumption rates per person, respectively.

2) Optimization of Light Intensity by the hour and Engery Consumption

The light intensity control problem is to find optimal illumination strategies for minimum the energy consumption in CELSS while maintaining sufficient oxygen level for human being. The parameters of KDDM are set according to calibration results [19]. The optimization objective is minimum total energy consumption of CELSS which is mainly caused by LED, as in (9):

$$J(I_0) = \int_0^D \alpha I_0 \mathrm{S_{plant}}\, dt \tag{9}$$

Where J is the computed total energy consumption, the unit is J; D indicates the total time during the CELSS integrated test (h), set to 720; α is a conversion coefficient from µmol photon m^{-2} s^{-1} to J m^{-2} s^{-1}, set to 0.2; I_0 is the light intensity. Besides, the light intensity (I_0) is under the following constraints due to meeting the demand of oxygen for crew, as in (10):

$$\frac{\mathrm{d}O_a}{\mathrm{d}t} \geq 0 \tag{10}$$

Obviously, the total energy consumption (J) is minimum when $\mathrm{d}O_a/\mathrm{d}t$ is equal to zero, i.e., $P_{\mathrm{gd}} = 30\lambda K_{\mathrm{O_2}}/32S_{\mathrm{plant}} + R_{\mathrm{m}}$ according to (8). Thus, the optimal light intensity can be calculated according to (2), (3) and (4), i.e., $I_0 = h^{-1}(P_{\mathrm{gd}})$, where h^{-1} is the inverse function of the daily crop gross assimilation rate (P_{gd}) with respect to light intensity (I_0). In this work, the time step used for the optimization of light intensity is 1 hour.

B. Experiment Materials and Measurements

Data were collected from a two-person-30-day CELSS integrated test from 1st Nov. to 1st Dec., 2012 in Beijing, China. The platform is tightly sealed which consists of a plant cabin, crew cabin, temperature and humidity control system, plant illumination system, nutrient solution control system, effluent collecting and disposing equipment, etc. Light emitting diodes (LED) were used as light sources which consisted of 90% red light and 10% blue light. The photoperiod was 24 *h*, with the photosynthetically active radiation (PAR) being 500 *µmol* m^{-2} s^{-1} at a distance of 30 cm below the light source. Collected (hourly) temporal data included air temperature, pressure and CO_2/O_2 concentration in the atmosphere of the cabin of CITP. During the 30-day experiment, the dry weight of leaf blades, petioles and stem were measured destructively at five stages along the growing period. The details can be found in the reference of [21].

III. RESULTS

A. Optimization of Light Intensity

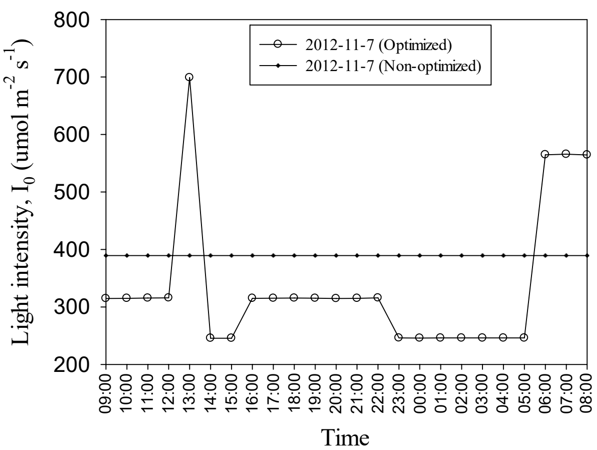

Fig. 4. The sequence values of optimized and non-optimized light intensities at the top of the plant canopy for 24 hours per day (Only results of Nov. 7, 2012 were shown).

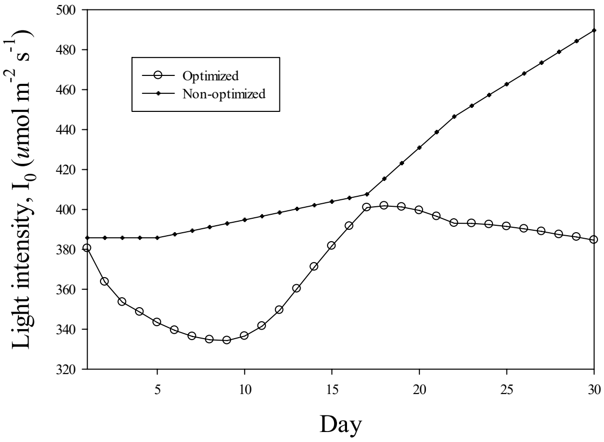

Fig. 5. The average values of optimized and non-optimized light intensities at the top of the plant canopy for the 30-day experiment.

Light intensity at the top of the plant canopy was optimized by the hour based on the KDDM approach. Curves of optimized and non-optimized light intensities for 24 hours of Nov. 7, 2012 during the 30-day experiment are shown in Fig. 4. Optimized light intensities by the hour show similar pattern: they rose in the day when crews were doing daily activity and reached the maximum value at 13:00 h due to physical exercises (the largest amount of CO_2 exhaled by the crew), then dropped in the night when crews were sleeping. However, non-optimized light intensities per hour did not vary with the amount of CO_2 exhaled by the crew during each day due to a fixed value. Besides, the average values of optimized and non-optimized light intensities at the top of the plant canopy each day are shown in Fig. 5.

B. Leaf Area Index

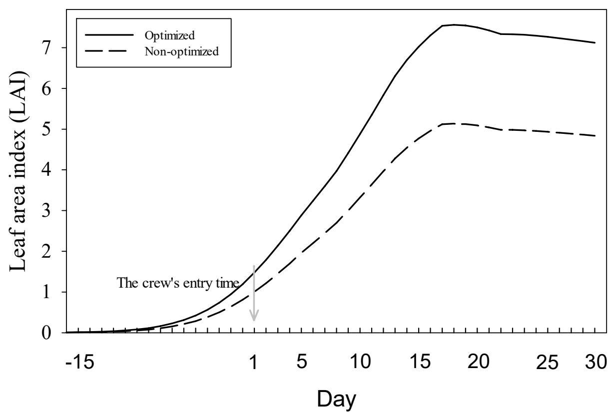

Fig. 6. Leaf area index under optimized and non-optimized light intensities.

Leaf area index increases with the growth of plant, as given in Fig. 6. Thus, the biomass production increases finally.

C. Total Dry Weights

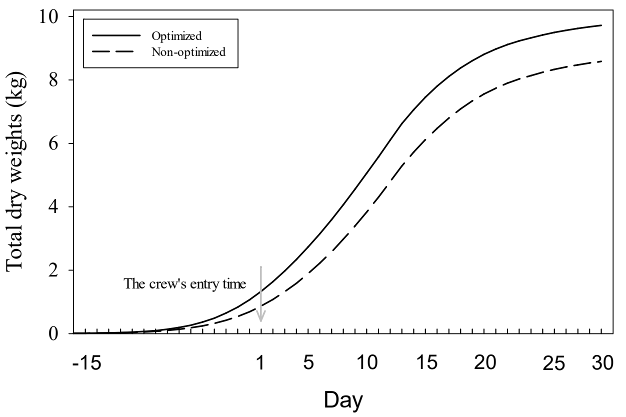

Fig. 7. Total dry weights under optimized and non-optimized light intensities.

The total dry weights under optimized and non-optimized light intensities were calculated for the 30-day (Fig. 7). As shown in Fig. 7, the total dry weights under optimized and non-optimized light intensities increased over time, reaching their maximum values of 9.72 kg and 8.59 kg, respectively, at final harvest. Note that their other environmental conditions are same. Compared to the situation under non-optimized light intensity, our optimization method increases the total dry weights of 13.2%.

D. CO_2/O_2 Concentration

During the 30-day experiment, both CO_2 and O_2 concentrations in the atmosphere of the cabin are stable (C_a = 682.5 ppm, O_a = 21.36 %).

E. Engery Consumption

The total energy consumption under optimized and non-optimized light intensities were computed for the 30-day according to (9). Compared to the previous experimental set without optimized light intensity, our optimization method can increase the light use efficiency of 11.5%.

TABLE II. COMPARISON OF ENGERGY CONSUMPTION BETWEEN NON-OPTIMIZED AND OPTIMIZAED LIGHT INTENSITIES.

	Total energy consumption (MJ)
Non-optimized light intensity	143.17
Optimized light intensity	126.76
Energy savings	11.5%

IV. DISCUSSION AND CONCLUSIONS

Using the knowledge-and-data-driven modeling (KDDM) approach, we can simulate plant growth and dynamic of CO_2/O_2 concentration in a closed ecological life support system of plant and human being. Based on that simulation, the aim of this study is to provide a scheme of light intensity control in order to determine the most suitable light intensity in CELSS for plant cultivation, which can minimum the energy consumption and meet the demand of plant production and oxygen for the crew in the meanwhile.

The biomass production increases under the optimal light intensity with the improvement of LAI (Fig. 7). The traditional light intensity did not take into account the differences of plant photosynthesis and respiration between the day and night.

Green plants can use the energy of light to remove carbon dioxide from the atmosphere and add oxygen to it while at the same time synthesizing food for the crew. The water that crop plants transpire can be condensed in pure form, contributing to the water-purification system. In this study, we set enough oxygen production as the optimal target to compute the demand of light intensity according to the activity of crew. For more complex system, the enough production of food and oxygen will be the optimal targets for computing light intensity, which will be controllable for that kind of system. In addition, recent advances in technologies and science bring new chances for the modeling of the CELSS [22-25]. Since system behaviors are dependent on crop species, how other plants behave in such system is also worthy to be studied as leafy plants are not sufficient to provide a full diet for human being. This approach provides a computational basis for life-time optimization of cabin design and experimental setup of CELSS.

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