AN INTELLIGENT CROP PLANNING TOOL FOR CONTROLLED ECOLOGICAL LIFE SUPPORT SYSTEMS

Final Report

NASA/ASEE Summer Faculty Fellowship Program -- 1995

Johnson Space Center

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NASA/JSC

Directorate:	Engineering
Division:	Automation, Robotics, & Simulation
Branch:	Intelligent Systems
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Date Submitted:	August 11, 1995
Contract Number:	NGT-44-001-800

ABSTRACT

This paper describes a crop planning tool developed for the Controlled Ecological Life Support Systems, CELSS, project which is in the research phases at various NASA facilities. The Crop Planning Tool was developed to assist in the understanding of the long term applications of a CELSS environment. The tool consists of a crop schedule generator as well as a crop schedule simulator. The importance of crop planning tools such as the one developed is discussed. The simulator is outlined in detail while the schedule generator is touched upon briefly. The simulator consists of data inputs, plant and human models, and various other CELSS activity models such as food consumption and waste regeneration. The program inputs such as crew data and crop states are discussed. References are included for all nominal parameters used. Activities including harvesting, planting, plant respiration, and human respiration are discussed using mathematical models. Plans provided to the simulator by the plan generator are evaluated for their "fitness" to the CELSS environment with an objective function based upon daily reservoir levels. Sample runs of the Crop Planning Tool and future needs for the tool are detailed.

INTRODUCTION

In order for the success of long duration manned missions into space, the concept of closed ecological life support systems (CELSS) are being explored by the National Aeronautics and Space Administration. Development of life support systems relatively independent of resupply are necessary for a reduction of launch weight and resupply penalties. Long duration missions will require autonomous systems capable of maintaining any series of internal environments, as well as regenerating wholesome food and air from waste materials (1). Within CELSS, gases such as oxygen and carbon dioxide and food can be described as reservoirs which must be maintained within some boundaries for the survival of both human and plant life. As well as maintaining adequate reservoirs, a CELSS has rigid system constraints such as space and time constraints. A CELSS environment contains physiochemical as well as biological functions such as food production. With these functions and the rigid system constraints of a CELSS, the long term dynamics of the system must be explored.

One primary concern of a system which relies on plant growth for food and gas reservoir balance is the long term planning and scheduling of crop planting. What crops to plant, when to plant, and how much to plant can affect the reservoir levels and the system constraints of a CELSS system weeks, months, or even years in the future. A Crop Planning Tool has been developed which addresses these long term implications of the CELSS environment. The Crop Planning Tool is comprised of a crop schedule generator developed by V. J. Leon (2) coupled with a crop schedule simulator. The purpose of the Crop Schedule Simulator is to provide a proof of concept simulator which will allow the Crop Schedule Generator to produce plans which are flexible and adaptable while providing maximum probability of survival for the crew. The Crop Schedule Simulator will be discussed here in detail while the algorithm for the Crop Schedule Generator will be touched upon briefly.

CROP PLANNING TOOL

The importance of crop planning for a CELSS is important for two reasons. First, what will be planted today will affect the crew's probability of survival tomorrow. Second, limited reservoirs and buffers in the CELSS environment make crop planning an important decision. The crop schedule decision is a difficult one because of the system constraints affecting a CELSS environment. These constraints can be grouped into the following areas: nutrient constraints, processing constraints, space and time constraints, and reservoir requirements. Nutrient requirements for both plants and humans must be met and balanced. This process requires proper food requirements and regeneration systems such as recycling of inedible biomass in order to recover valuable minerals and nutrients for plants. Obeying constraints on processes such as harvesting and planting by humans or robots is necessary while taking into account other daily maintenance and research activities on the part of the crew. Space and time constraints are vital to the balance of a CELSS because limited planting space and storage buffers exist. While satisfying these constraints, a CELSS environment must maintain adequate reservoirs of gases such as oxygen and carbon dioxide, water, and amounts of fresh and stored edibles.

SIMULATOR

The Crop Schedule Simulator, which will be referred to as the Simulator, requires the initial state of the system as well as a crop planting schedule provided by the Crop Schedule Generator (2), which will be referred to as the Planner. The initial state of the system includes information pertaining to the crew, crops, and the environment. The plan which is obtained from the crop planner module is integrated with the initial state to simulate the activities of the CELSS over some ΔT time period. The outcome of the simulation is then evaluated to obtain an objective function for the overall fitness of the plan. The

Simulator also calculates any adjustments required by the CELSS system. For example, the Simulator might suggest increased efficiency in the waste regeneration systems. These changes will be reflected in the waste processing parameters.

Assumptions

In developing this proof of concept Crop Planning Tool, several assumptions have been made.

- The Simulator developed here tracks solely oxygen and carbon dioxide levels. Other vital resources such as water and nutrients have not been modeled.
- Two crop models are utilized and therefore, two planting options exist, either wheat or lettuce.
- Within a time slice (1 day for this implementation) average growth rates of plants and activity levels of crew members are assumed. It is assumed that there exists a constant hour to hour monitoring and control system which maintains target gas concentrations in the air.
- With the existence of a monitoring and control system, the Planner and Simulator will consider only tank levels and not in air concentrations.

INPUT -- INITIAL STATE

Capturing the initial state of the CELSS is vital for two reasons. One, the outcome of the system depends on the initial state of that system. Futhermore, detailing an initial state allows dynamic planning capabilities. The initial state can be categorized in five main areas: Reservoir Levels, Crew Information, Crop States, Crop Historical Data, Waste Processing Parameters.

Reservoir Levels

Reservoir levels are required for gases and crops in the system. Inputs include the initial storage level of each type gas or crop, the minimum reservoir level, the nominal reservoir level, and the maximum reservoir level. These values can vary for design purposes.

Crew Information

Crew data requirements include:

- Average Metabolic Rate (BTU per hour)
- Respiratory Quotient
- Food Requirement (kg per person per day)
- Menu Desires: Rating factor for the proportion of each type of crop which the crew desires for consumption
- Average Oxygen Generation and Carbon Dioxide Production Rates (kg per person per day)
- Crew Member Profile: Number of crew members per day

Table 1 indicates the values used for each crew data requirement above and the associated reference.

TABLE 1. CREW DATA REQUIREMENTS

DATA	VALUE	REFERENCE
Average Metabolic Rate	619 (BTU/hour)	3
Respiratory Quotient	.90	3
Food Requirement	.800 (kg/person - day)	4 (based on wheat as only provider)
Average Oxygen Generation and Carbon Dioxide Production Rates	1.096 Oxygen 1.356 Carbon Dioxide (kg/person - day)	3
Crew Member Profile	See Reference	5

Crop States

The Simulator is also given the initial state of crops which are in planting. The Simulator tracks the state of trays in "batches". Each batch of plants is of a particular plant type and the batch was planted or is scheduled to be planted at the same time. The information required of each batch in planting is the following: number of trays associated with the batch, time the batch was planted, plant type of the batch. These batches can then be preprocessed with general parameters utilized for a plant of its particular plant type. For instance, plant density (plants/m^2), temperature of the biom (°C), and edible/inedible biomass ratios are associated with each batch. General plant model parameters are discussed in (6).

Crop Historical Data

Each crop model utilized in the simulation produce rates of oxygen production and carbon dioxide use as well as biomass production rates. Using these models, historical data is compiled by the Simulator to be used in long term planning by the Planner. Table 2 summarizes this data. A storage conversion is also necessary to check storage limits of edible food.

TABLE 2. HISTORICAL CROP PARAMETERS

DATA	Wheat	Lettuce	REFERENCE
Edible Biomass at Harvest	0.424 (kg/m^2)	2.115 (kg/m^2)	6, 7, 8
Inedible Biomas at Harvest	2.230	0.235	6, 7, 8
Total Biomass at Harvest	2.654	2.350	6, 7, 8
Growth Cycle	80 days	30 days	7
Storage Conversion	0.001 m^3/kg edible	0.003 m^3/kg edible	7

Total biomass at harvest data was obtained from the Wheat and Lettuce Crop Growth Models in (6). The amount of edible biomass obtained from the total biomass at harvest for wheat varied widely from 16% in (8) to 45% in (4). For the general wheat plant, 16% was used.

Waste Processing Parameters

Waste processing parameters are necessary from the system to determine how efficiently the waste regeneration system performs. Human waste processing rates and plant waste processing rates were derived from (4). During the simulation, reservoirs of oxygen and carbon dioxide must be adjusted to account for waste processing.

The amount of oxygen used for waste processing and the amount of carbon dioxide generated by human and plant waste processing can be broken down into human waste and plant waste requirements using the ratio of human or plant waste to the total waste from both sources. These ratios can then be used to breakdown the amount of oxygen and carbon dioxide used and given off respectively from waste processing due to plant waste and human waste. Gas generation and utilization rates due to the processing of human and plant wastes were found using (4). For example:

Carbon dioxide given off due to processing human wastes:

$$\left(\frac{(.16136)}{(.16136+1.04475)}\right)2.33452 = 0.313 kg/p-d$$

(All numbers are in units of kg / p - d which refers to kilograms per person per day)

Carbon dioxide given off due to processing plant wastes:

$$\left(\frac{(1.04475)}{(.16136+1.04475)}\right)2.33452 = 2.023 kg/p-d$$

Similarily, oxygen utilized due to human waste processing was found to be 0.288 *kg / p - d*. Oxygen utilized due to plant waste processing was found to be 1.866 *kg / p - d*. In order to look at the mass flows concerning plants, the mass units can be converted into kilograms per meter squared (in order to take into account a specific area of plants). Using these values, the amount of carbon dioxide generated in waste processing due to plants can be found using the following ratios:

$$\left(\frac{2.023kg/p-d(CO_2 forplantwaste)}{1.045kg/p-d(plantwaste)}\right)=1.936\frac{kg(CO_2 forplantwaste)}{kg(plantwaste)}$$

Similarily, the amount of oxygen utilized by the waste processing of inedible plant mass is found using the following ratios:

$$\left(\frac{1.866kg/p-d(O_2 forplantwaste)}{1.045kg/p-d(plantwaste)}\right)=1.786\frac{kg(O_2 forplantwaste)}{kg(plantwaste)}$$

These values were found based on amounts of inedible biomass at harvest. Therefore, the model discussed here will adjust reservoir levels of oxygen and carbon dioxide when plants are harvested.

INPUT -- A PLAN

A plan consists of the following: What crop to plant, How much to plant, When to plant. The plan is generated by the Crop Schedule Generator and is delivered to the Simulator in the form of an event list.

SIMULATOR OUTLINE

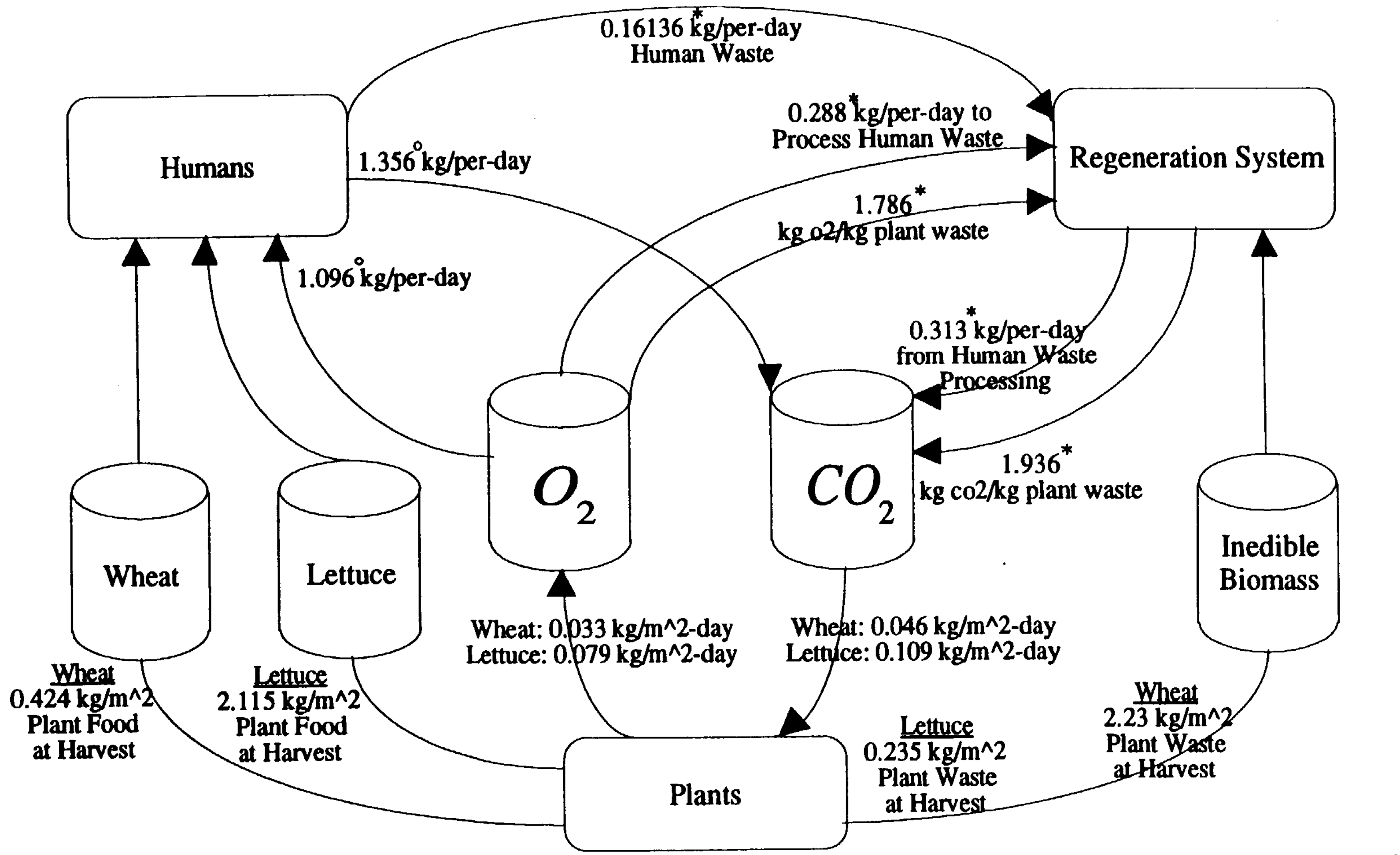
The simulation updates critical reservoirs daily. Activities required daily which effect these reservoirs include: harvesting, planting, plant respiration, human respiration, human consumption, and adjustments to reservoirs. Figure 1 depicts the overall model of a CELSS with average data abstracted from the human and plant models used in the Simulator. Figure 2 depicts the simulation flow. Any harvesting or planting required in each time period are simulated. At harvest, edible and inedible biomass ratios are utilized to calculate the amount of food and wastes in kilograms obtained from each harvested batch. The food level of the crop is then adjusted, and oxygen and carbon dioxide tank levels are appropriately adjusted for waste processing of inedible biomass resulting from each harvest.

PLANT RESPIRATION

Plant respiration simulates plants producing oxygen and using carbon dioxide. For these purposes, the biomass rate models for wheat and lettuce developed in (4) are used. The plant respiration function therefore, not only simulates the respiration of plants, but also simulates their growth. In this manner, biomass is accumulated over each plant's growth cycle.

Wheat Model

Miller, McFadden, and Sirko (4) developed the biomass production model utilized by the Simulator. The wheat model is valid for a specific range of environmental parameters documented in (4). The first step in the wheat model is to determine the development rate in terms of crop age and



° (3)
* (4)
All others (6)

Wheat: Eb = .16 IEb = .84 (8)
Ave. Biomass at Harvest = 2.65 kg/m^2
Lettuce: Eb = .90 IEb = .10 (7)
Ave. Biomass at Harvest = 2.35 kg/m^2

Figure 1. CELSS World Model with Plant Model Data

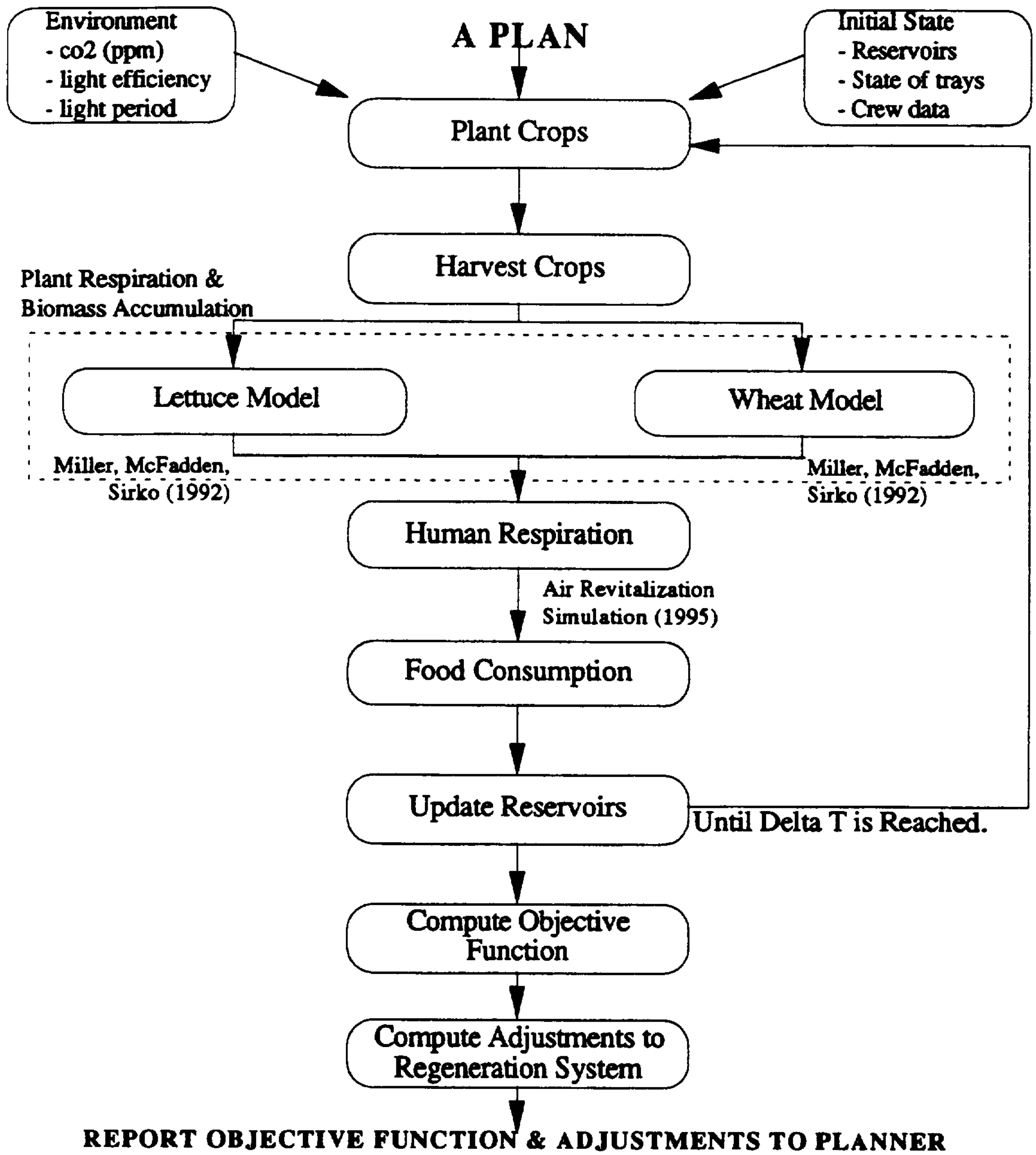


Figure 2. Simulator Block Diagram

temperature. In order to introduce the effect of photoperiod, the development rate is adjusted by a ratio of the nominal photoperiod (hours) to the daily daylight interval (hours). The age, temperature, and photoperiod dependent crop development rate can then be written:

$$r(T,\tau;t) = a_1 + \frac{a_2(t)(\tau)}{\tau_N} + \frac{a_3(t_l)^2(\tau)^2}{\tau_N^{\,2}} \qquad \begin{aligned} a_1 &= -3.782 + 0.3.56T \\ a_2 &= 0.24696 + 0.2515T \\ a_3 &= 0.06175 - 0.006866T \end{aligned}$$

where $\tau =$ Daily Daylight Interval, $\tau_N =$ Nominal Photoperiod (20 hr), and t = Crop Age. Other effects such as light intensity and carbon dioxide concentration are taken into account. The average biomass rate $B(A)$ is found where A is the photosynthetic active radiation provided by the lights. The photosynthetic active radiation is scaled by the canopy's age. The average biomass rate is then written:

$$B(A_L) = -7.6146 + 0.11114A_L - 0.00002149A_L^{\,2}$$
$$A = ((160)(Eff)(Conv)(Y))/a$$
$$A_L = A - (1.167(H))$$

where Eff = Electrical efficiency of the lights (0.095 nominally), $Conv$ = µmol/J for lights (4.59 for cool white fluorescent lights), a = Area of each plant growth tray(m^2), and H is the height of the lights above the crop canopy(cm). The crop development rate is then scaled to take the average biomass production rate into account by:

$$r(T,\tau,A;t) = r(T,\tau;t)\frac{B(A_L)}{B(A_N)}$$

where A_N = 1204µmol/m^2-sec and $B(A_N)$ = 95 grams/m^2-day. In order to incorporate the effect of carbon dioxide concentration, the net photosynthesis $C(p)$ in µmol/m^2-sec is found and then integrated into the crop development rate. Finally, to account for varying plant density a scaling factor is integrated into the crop development rate. The crop development rate is found in grams/m^2-day.

$$C(p) = 72.0 - 78.89/e^{p/400}$$

$$r(T,\tau,A,p,d;t) = r(T,\tau,A;t)\frac{C(p)}{C(p_N)}\frac{d}{d_N}$$

where p = Carbon dioxide concentration in the air, p_N = Nominal carbon dioxide concentration(2000 ppm), $C(p_N)$ = 71.47 µmol/m^2-sec, d = Plant density (plants/m^2), and d_N = Nominal plant density (2000 plants/m^2). The corresponding carbon dioxide and oxygen rates were found by Miller, McFadden, and Sirko using a generalized photosynthetic equation. From these equations, it was determined that for 1 gram of biomass produced 0.727 grams of oxygen are produced and 1.381 grams of carbon dioxide are assimilated.

Lettuce Model

Miller, McFadden, and Sirko (4) developed a mathematical model for carbon dioxide assimilation for Waldman's green lettuce. The model developed is a function of the carbon dioxide concentration in the air, x, the light intensity, y, and crop age, t. The carbon dioxide assimilation can be written:

$$r_{CO_2}(t,x,y) = r(t)g(x,y)$$

If $t < 11$ days,

$$r(t) = 0.31752$$

Else if $11 < t < 30$,

$$r(t) = 26.72 - 5.45t + 0.341t^2 - 0.0059t^3$$
$$CO_2N = -3.333 + 0.00333x$$
$$LTN = -3.0 + 0.5y$$

$$g(x,y) = 1.0 + 0.12CO_2N + 0.354LTN - 0.0732LTN^2$$

where $r(t)$ is the nominal carbon dioxide assimilation as a function of crop age in grams per hour, $g(x,y)$ is the off-nominal carbon dioxide assimilation as a function of carbon dioxide concentration in the air and light intensity in grams per hour, and CO_2N and LTN are normalized carbon dioxide concentration and light intensity, respectively. The model only applies within specific parameter ranges (4). Moreover, prior to day 11 in the growth cycle of a lettuce plant, a constant rate of carbon dioxide assimilation is used which is equal to the nominal assimilation rate for an 11 day old lettuce plant, 0.3175 grams per hour. The corresponding biomass production and oxygen production rates were found by Miller, McFadden, and Sirko using a generalized photosynthetic equation. From these equations, it was determined that for 1 gram of carbon dioxide assimilated 0.727 grams of oxygen are produced and 0.723 grams of dry biomass are produced.

HUMAN RESPIRATION

The human respiratory model used in the Simulator was developed at the Johnson Space Center for an Air Revitalization Simulation for a CELSS environment (3). The model utilizes the human respiratory quotient, RQ, and metabolic rate, MR, to produce an oxygen use rate in kilograms per person per day and a carbon dioxide generation rate in kilograms per person per day. An average metabolic rate is utilized to calculate average gas rates daily. It is assumed that a real time control and monitoring system would account for hourly metabolic profiles.

$$O_2(lb/person-hour) = [0.1708 - (RQ - 0.707)/0.293)(0.0123)](MR)$$
$$O_2(kg/person-day) = (10.88)O_2(lb/person-hour)$$
$$CO_2(kg/person-day) = (44/32)(RQ)(O_2(kg/person-day))$$

HUMAN CONSUMPTION

In order to simulate the depletion of food reservoirs through human consumption, the idea of menus was introduced. Delivered to the Planner and Simulator are menu preferences by the crew. The menu is a ranking of what portions of each type crop would be desired for the crew's daily food requirement. The consumption function is called daily by the Simulator. The consumption function follows the outline below:

(A) Calculate the total daily food requirement for the crew.

(B) While all food reservoirs are not depleted and the total daily requirement is not met:

- (i) Update menu desires. Recalculate where needed for depleted reservoirs.
- (ii) Deplete each reservoir according to daily requirements and preferences.

The Simulator not only keeps track of food levels for each crop but in addition, tracks how much edible storage remains of each harvested batch. Therefore, as food levels are depleted, batches are depleted accordingly. The Simulator depletes batches on a first-in, first-out (FIFO) basis. With FIFO in mind, initial food reservoirs are depleted first.

UPDATING RESERVOIRS

Every time period or time slice (1 day in this implementation), reservoirs of gases and food must be updated to reflect the planting, harvesting, respiration, and consumption processes. Food levels are adjusted accordingly as plants are harvesting and food is consumed. Gas levels are adjusted at the end of each time period. The following equation is used to update oxygen and carbon dioxide reservoirs.

Gas Level (t) = Gas Level (t - 1) +/- Gas to Process Human Waste +/- Gas to Process Plant Waste + (Gas Generated - Gas Used)

ADJUSTMENTS

After the Simulator completes the emulation of a plan, various parameter adjustments can be computed. Currently, the Simulator recalculates the waste processing needs for plant wastes. Looking at the trends in oxygen and carbon dioxide tank levels, the Simulator can calculate what waste processing needs would be required in order to obtain nominal gas levels. In order to calculate these adjustments to waste processing parameters, the following formulation is used for each gas:

$$Change = \left(\frac{\sum_{t=t_S}^{t_F} Gas(t) - Gas(t-1)}{t_F - t_S} \right) \left(\frac{t_F - t_S}{\sum_{t=t_S}^{t_F} Harv(t)} \right)$$

where $Gas(t)$ is the gas level at time t, t_F is some specified finish time to end summing deviations, t_S is a specified start time to begin summing deviations, and $Harv(t)$ is the amount of inedible biomass obtained from harvesting in time period t. The start and finish times are used to establish a "warm up" period for data collection.

OBJECTIVE FUNCTION

In order to establish the overall "goodness" of a plan, an objective function was developed which is a function of the vital reservoir levels in the CELSS. Currently, the Simulator considers oxygen, carbon dioxide, wheat, and lettuce levels in these calculations. In order for crew and plant life to be maintained in a CELSS, reservoir levels must be maintained within certain desirable limits. Because levels too low or too high could put the CELSS environment in jeopardy, the objective function penalizes reservoir levels above and below the nominal reservoir levels. First, average deviations from nominal levels are calculated and they are then scaled by the deviation of the maximum and nominal limits. Large deviations are then penalized by a power. The objective function is written as follows:

For $R = 0$ to the number of critical reservoirs, N :

$$D_R = \left(\frac{\left[\sum_{t=0}^{M} \left[\frac{RL(t) - RL_N}{RL_{MX} - RL_N} \right]^{PW} \right]}{M} \right)^{1/PW}$$

$$ObjectiveFunction = \left(\frac{\sum_{R=0}^{N} (D_R)^{PR}}{N} \right)^{1/PR}$$

where D_R is the deviation for each reservoir, M is the amount of time simulated, $RL(t)$ is the reservoir level at time t, RL_N and RL_{MX} are the nominal and maximum reservoir levels, and PW and PR are variables used to penalize large deviations from nominal.

CROP SCHEDULE GENERATOR

The Crop Schedule Generator was implemented following the approach suggested by V. J. Leon (2). The procedure *Planner()* is summarized in the following pseudo-algorithm:

```
Procedure Planner():
    do{
        tnow = tnow + Next_time_incr();
        Update_reservoir();
        Get_donothing_levels(LOOKAHEAD);
        Diagnose_situation();
        Get_desire_probability();
        Repeat for NTRIALS {
            What_to_plant();
            Local_evaluation();
            Save_best();    }
    } while (tnow < PLANNING_HORIZON)
```

Next_time_incr(). This function determines when the next scheduling decision will be made. In the current implementation this time is determined by the following events: (1) next crop ready for harvest, (2) the pre-specified cycle (e.g. WHEAT_CYCLE or LETTUCE_CYCLE) for a given crop when there are empty trays.

Update_reservoir(). This function updates all reservoir levels based on the previous planting decision and the time increment determined in *Next_time_incr()*.

Get_donothing_levels(). This function determines the reservoir levels for the next LOOKAHEAD time units if no planting takes place at time tnow.

Diagnose_situation(). Given the *do-nothing* alternative, this function is used to alert the user on the possible problems in the near future. This information can be used for schedule explanation and during schedule decision making.

Get_desire_probability(). This function computes the desirability probability distribution by assuming that a single crop will be planted on all available trays. The impact of this decision is evaluated from time 0 to the next LOOKAHEAD time units. The *do_nothing* action is considered as one of the possible actions. The output of this function is a probability distribution which reflects how desirable it is to plant a given crop type or do-nothing.

The following three procedures are a simplistic approach to search for a good alternative:

What_to_plant(). Using the desirability probability distribution, empty trays are randomly assigned crop-types (including *do_nothing*). Care is taken not to exceed the maximum allowable batch size, (e.g. MAX_WHEAT, MAX_LETTUCE) - if a maximum is reached, the tray is left empty and rescheduled for consideration at the next crop cycle (e.g. WHEAT_CYCLE time units later).

Local_evaluation(). The planting decision made in *What_to_plant()* is evaluated from time 0 up to tnow + LOOKAHEAD time units.

Save_best(). The best decision found in the NTRIAL trials is added to the partial schedule and used to continue the generation process.

Clearly, better solutions can be searched for using more elaborated search procedures. This however is out of the scope of the project and is an interesting direction for future research.

EXAMPLE RUNS

Using the Crop Planning Tool, several runs were made which illustrate the applications of the Crop Planning Tool. A sample of the different scenarios analyzed include:

- Comparing the effects of different amounts of growing area available
- Comparing different crew profiles over a mission life
- Comparing baseline waste processing parameters to the parameters as suggested by the Simulator after an initial run
- Comparing light intensities available to wheat by changing the number of light bulbs per tray
- Comparing different inedible and edible biomass ratios for wheat

Several of these scenarios are depicted in Figures 3 - 6. The food and gas levels are illustrated for each scenario. These examples illustrate the design implications of the Crop Planning Tool. The tool could be utilized to plan for future missions or in the design of a CELSS. The baseline scenario is based on the crew profile outlined in (5), 300 trays for growing at 0.88 m^2 (264m^2 growing area), nominal values for wheat and lettuce parameters, nominal waste processor values, and nominal crew data values as outlined in INPUT -- INITIAL STATE above.

FUTURE NEEDS

Future needs for the Crop Planning Tool include:

- A friendly user interface for parameter changes and the corresponding outcomes to be viewed quickly by the user.
- Additional crop models including more advanced crop models which illustrate gradual harvest crops.
- Integration of the tool with a control and monitoring system as well as a low level task sequencer and resource allocater.
- Critical reservoirs such as water, nutrients, etc. should be included for a more robust world model.
- Model robustness could be improved with real time data from NASA experiments currently in process.
- Processes such as the waste processing system should be modeled explicitly to gain a deeper understanding of the CELSS waste regeneration requirements.

All of these needs stated and more would improve the Crop Planning Tool as a design tool and an evaluation tool for current CELSS environments.

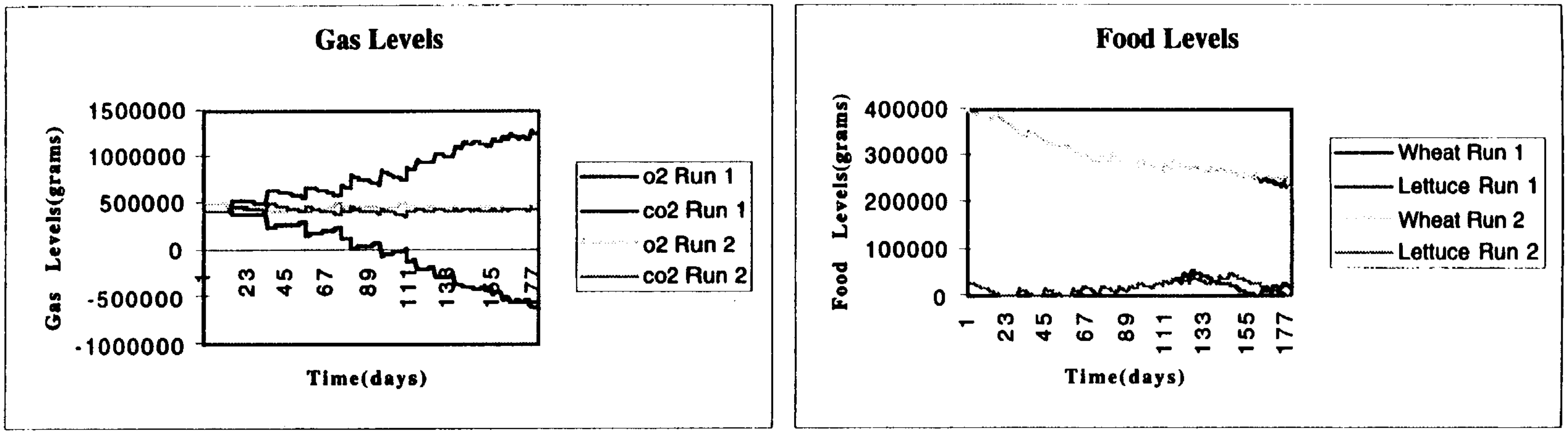


Figure 3 and Figure 4. Gas Levels and Food Levels for Baseline vs. Waste Processing Parameter Change.
Run 1: Baseline with waste processing parameters: 0.288 kg o2/kg-pers-day, 0.313 kg co2/kg-pers-day, 1.786 kg o2/kg plant waste, 1.936 kg co2/kg plant waste.
Run 2: Simulator suggested waste processing parameters: 0.288 kg o2/kg-pers-day, 0.313 kg co2/kg-pers-day, 0.619 kg o2/kg plant waste, 1.011 kg co2/kg plant waste.

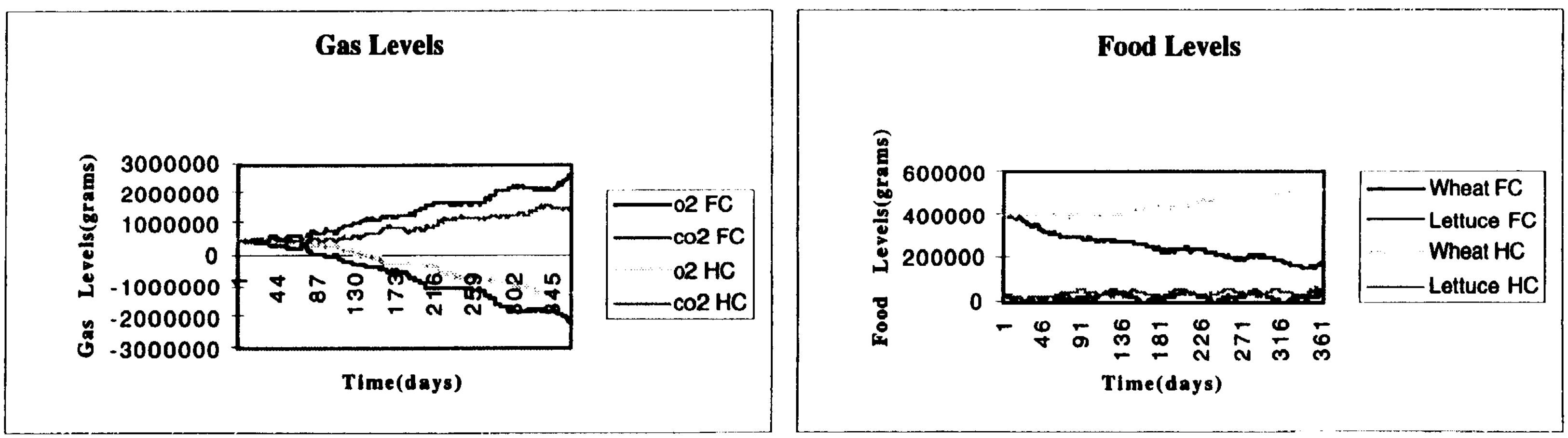


Figure 5 and Figure 6. Gas and Food Levels for Baseline with Full Crew vs. Half Crew Profile.
Run 1: Baseline scenario with full crew profile as stated in (5) for 364 days.
Run 2: Baseline Scenario with half crew profile (2 crew members for 364 days.

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REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY (Leave Blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	August 1996	NASA Contractor Report

4. TITLE AND SUBTITLE

National Aeronautics and Space Administration (NASA)/American Society for Engineering Education (ASEE) Summer Faculty Fellowship Program - 1995 (Volumes 1 and 2)

5. FUNDING NUMBERS

NGT 44-001-800

6. AUTHOR(S)

William A. Hyman* and Donn G. Sickorez, Editors

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Lyndon B. Johnson Space Center
Office of Public Affairs
Houston, Texas 77058

8. PERFORMING ORGANIZATION REPORT NUMBERS

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Washington, D. C. 20546-0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

CR-201377

11. SUPPLEMENTARY NOTES

*Texas A&M University, College Station, Texas

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Unclassified/Unlimited
Available from the NASA Center for AeroSpace Information (CASI)
800 Elkridge Landing Road
Linthicum Heights, MD 21090-2934
(301) 621-0390

Subject Category: 99

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

The JSC NASA/ASEE Summer Faculty Fellowship Program was conducted at JSC, including the White Sands Test Facility, by Texas A&M University and JSC. The objectives of the program, which began nationally in 1964 and at JSC in 1965, are (1) to further the professional knowledge of qualified engineering and science faculty members; (2) to stimulate an exchange of ideas between participants and NASA; (3) to enrich and refresh the research and teaching activities of the participants' institutions; and (4) to contribute to the research objectives of the NASA centers. Each faculty fellow spent at least 10 weeks at JSC engaged in a research project in collaboration with a NASA/JSC colleague. In addition to the faculty participants, the 1995 program included five students. This document is a compilation of the final reports on the research projects completed by the faculty fellows and visiting students during the summer of 1995. The reports of two of the students are integral with that of the respective fellow. Three students wrote separate reports.

14. SUBJECT TERMS

information transfer, research, research projects, engineering, science, university program

15. NUMBER OF PAGES

428

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	Unlimited

NSN 7540-01-280-5500

Standard Form 298 (Rev 2-89)
Prescribed by ANSI Std. 239-18
298-102