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Summary

A Controlled Ecological Life Support System (CELSS) utilizes a plant's natural ability to regenerate air and water while being grown as a food source in a closed life support system. Current plant research is directed toward obtaining quantitative empirical data on the regenerative ability of each species of plant and the system volume and power requirements. Two techniques were adapted to optimize crop species selection while at the same time minimizing the system volume and power requirements. Each allows the level of life support supplied by the plants to be selected, as well as other system parameters. The first technique uses decision analysis in the form of a spreadsheet. The second method, which is used as a comparison with and validation of the first, utilizes standard design optimization techniques. Simple models of plant processes are used in the development of these methods.

Introduction

To date, life support technology is based solely on physical/chemical processes, and this is likely to remain true for the initial phases of the Space Exploration Initiative. However, for long-duration missions, such as a trip to Mars or long-term habitats on the Moon or Mars, a Controlled Ecological Life Support System (CELSS) has the potential to provide human life support with significant cost and safety benefits over the currently envisioned physical/chemical systems. In particular, the amount of food resupplied from Earth may be significantly diminished, higher plants can accomplish both air revitalization (through the release of oxygen and uptake of carbon dioxide) and water processing (through transpiration), and some waste disposal may be accomplished biologically. Figure 1 shows an example of an integrated biological and physical/chemical life support system. Other studies have resulted in variations on this conceptual design (refs. 1-3).

Normally, a trade study is conducted to determine advantages and disadvantages of various design options. Trade-study techniques can be developed in parallel with research on basic performance parameters, so that when reliable data become available, the analysis tool is also ready to perform trades. These tools will become increasingly important as we begin to address the complexities involved in integrating biological components with physical/chemical life support system components.

To date, most research in the use of plants for life support has concentrated on productivity levels and the effects of environmental parameters on productivity. Little work has been done in evaluating the air and water regeneration and waste management capabilities, which would be the next logical step toward developing an integrated life support system. The techniques outlined herein transform newly acquired plant performance data into parameters describing a CELSS for use in trade studies, thus providing the link between generating data and developing an optimal CELSS design.

We are adapting two techniques to optimize crop selection for minimum power and volume penalties. The first technique involves the use of decision analysis which implements a decision tree. The second method, intended to be both a comparison with and a validation of the first, involves the use of standard design optimization (linear programming) techniques. Previously, design optimization techniques have been applied to crop mix selection to select the minimum crop area which satisfies human nutritional requirements (ref. 4). While the results of that study do not account for power penalties, nor do they allow for air and water regeneration constraints, some comparisons can be made with our own data. These comparisons are reported in the Results section of this paper.

A spreadsheet is used as an interface with the user and to generate plant and system parameters. The user specifies the level of life support to be supplied by the plants for each life support function—oxygen generation, carbon dioxide uptake, water regeneration, and nutrient (carbohydrate, lipid, and protein) production. Plant parameters are generated both directly from empirical data input by the user and from models of plant processes. However, the techniques are intended to be generic and applicable to other plant parameter generation schemes.

Approach

Derivation of Plant and System Parameters for Input to Analyses

Parameters specifying system requirements are input into the spreadsheet section shown in table 1. Here the user can input which crops of those whose performance data have been entered into table 2 should be considered. Up to five crops can be chosen. If variety in the crop mix is desired, a minimum number of crops can be entered (a number greater than one will force multiple crops to be chosen). Currently this feature applies only to the decision analysis method. The level of life support to be fulfilled by plants and the daily life support requirements (ref. 5) are input into table 1, as well as the power and volume penalties (refs. 6 and 7) and end-to-end lighting efficiency.

Table 2 lists parameters which were obtained from the literature and other sources of plant data (refs. 8-12).[1] These parameters include each species' rate of transpiration and biomass growth as well as diet composition, edible fraction, and chamber height requirement. The lighting level and photoperiod under which these rates have been measured are also recorded and used for the power requirement calculations. There are a myriad of other factors that influence plant productivity, transpiration rates, edible fraction, and even diet composition, such as carbon dioxide level, oxygen level, nutrient solution composition, temperature, and humidity. These influences could be added in a more sophisticated effort to derive the parameters for the analyses input, but are not necessary for our purposes of technique development and demonstration.

Table 3 lists the parameters describing plant species' performance required by the optimization methods. Generation of these parameters can be accomplished in many different ways, from using empirical data to employing modeling techniques. We have elected to use a combination of these two methods, largely because gas exchange data for plant species are limited. Parameters which are more readily available from empirical data are used directly and as the basis for some simplified relations used to generate the remaining parameters.

Transpiration rate and biomass production rate are taken directly from the empirical data recorded in table 2. The fat, carbohydrate, and protein production rates are products of the biomass generation rate, $\dot{m}_{bio}$, the edible fraction, and the fraction of the total biomass generation, which is fat, carbohydrate, and protein, respectively.

$$\begin{bmatrix} \text{fat generation} \\ \text{carbohydrate generation} \\ \text{protein generation} \end{bmatrix} = \dot{m}_{bio} * \left(\begin{matrix} \text{edible} \\ \text{fraction} \end{matrix} \right) * \begin{bmatrix} \text{fat fraction} \\ \text{carbohydrate fraction} \\ \text{protein fraction} \end{bmatrix}$$

Carbon dioxide and oxygen generation rates are products and reactants of photosynthesis and respiration, as is biomass production. This link between biomass production and gas exchange rates is described by the photosynthetic equation, assuming respiration is ignored.

The chemical reaction of photosynthesis varies with the biomass type being formed, whether it is fat, carbohydrate, or protein. For simplicity, here it is assumed that carbohydrate is the substance formed. The photosynthetic equation describing carbohydrate formation is (ref. 13)

$$6CO_2 + 6H_2O \rightarrow C_6H_{12}O_6 + 6O_2$$

This equation gives the ratio of moles of carbohydrate produced to moles of carbon dioxide taken up and oxygen released. Converting these mole fractions to mass fractions (using the corresponding molecular weights), the oxygen generation rate, $\dot{m}_{O_2}$, and the carbon dioxide take-up rate, $\dot{m}_{CO_2}$, are related to the biomass production rate, $\dot{m}_{bio}$, by

$$\dot{m}_{O_2} = 1.0667\ \dot{m}_{bio}$$

$$\dot{m}_{CO_2} = 1.4\ \dot{m}_{bio}$$

The power requirement is determined using the lighting level recorded in table 2 measured as Photosynthetic Photon Flux (PPF), the radiation given off by the lights in the wavelength band useful for photosynthesis; the photoperiod, which is the hours each day that light is supplied to the plants; and the lighting system efficiency, η, which is the end-to-end efficiency of the lighting system. The equation used to calculate the required power, P_{REQ}, is

$$P_{REQ} = \frac{PPF * \text{photoperiod}}{\eta}$$

We have not incorporated optimum lighting levels for crops in this study. For a legitimate application of these techniques, data representing crops at optimal conditions must be entered into table 2 or a more sophisticated, compensating model must be devised. Alternatively, multiple entries of the same crop species could be made with parameters reflecting the crop's performance when optimized for biomass production, transpiration, power, or volume conservation.

The final calculation is the total cost. This is the sum of the power and volume (height times $1\,m^2$) times their corresponding penalties as given in table 1.

[1]Crops X and Y in table 2 have been added to enlarge the database. These two "species" are not real; the data from them merely illustrate the development of this tool.

$$\text{Total cost} = (P_{REQ})(\text{Power penalty}) + (\text{Volume})(\text{Volume penalty})$$

Note that this function could be made more sophisticated by weighting the relative importance of the two requirements or by adding mass as an additional cost. Whereas mass penalties could easily be incorporated into the cost function, current understanding of mechanically optimized plant chamber mass is sufficiently limited to defer incorporating mass penalties into this study.

Decision Analysis Method

Decision analysis methods described in reference 14 provide a tool for making decisions based on a single principal value (in our case, we have chosen to express everything in terms of cost). Most often, the tool used in decision analysis is a decision tree, where all possible outcomes and all possible paths to these outcomes are diagramed. Many decision-tree analyses also have expected values or probabilities attached to each branch stemming from a decision or node. In our case, we are merely minimizing cost at each decision node, with equal probability that any particular pathway will be followed. The decision tree (fig. 2) is constructed such that the initial decision determines which crop selection is the cheapest for all permutations of solutions having the same number of crops. A second round of decision-making is then done to determine the most economical number of crops one could use.

Computation of the cost values is shown in table 4. The assumption is made that an equal area is allotted to each crop in a crop mix. Thus the generation/dissipation rates of the plant products, power, volume, and cost are averages of the individual crops in a crop mix computed on a per-square-meter basis. The penalties incurred by this assumption are shown through the comparison of results with the results from the design optimization method, where this assumption is not required. The required generation/dissipation rates (calculated from the human requirements and the degree of support specified in table 1) are divided by the productivity of each crop mix to obtain the scaling factor (planting area in square meters) required to meet the specified level of life support. The largest scaling factor encountered for a particular crop mix is multiplied by the cost of the crop on a per-square-meter basis to obtain the cost penalty entered in the decision tree.

A feature of the decision-tree tool is the accessibility of cost values for all crop mixes. This allows the designer to investigate the cost of nonoptimal solutions, which might have more appeal than the optimal solution for qualitative reasons. For the example shown in figure 2, increasing the crop variety by selecting the most optimal four-crop solution over the three-crop solution increases the cost by 18%. Also, if a designer preferred wheat over potatoes in the optimal crop mix of lettuce, potatoes, and Y (crops 1, 2, and 4), the decision tree shows an increase in cost of 14% for lettuce, wheat, and Y (crops 1, 3, and 4).

Design Optimization Method

An alternative to using the decision analysis method described above is to take a design optimization approach (refs. 15 and 16). One can then minimize the cost function while removing the assumption of equal crop growth areas. For example, we use a linear programming approach to solve the constrained optimization problem

$$\min_{\text{area}} \left\{ \sum_{i=1}^{N} (\text{cost})_i (\text{area})_i \right\}$$

Subject to the following constraints

$$\sum_{i=1}^{N} \left(\frac{H_2O \text{ transpired}}{\text{area}} \right)_i (\text{area})_i \geq H_2O \text{ transpiration requirement}$$

$$\sum_{i=1}^{N} \left(\frac{CO_2 \text{ removed}}{\text{area}} \right)_i (\text{area})_i \geq CO_2 \text{ removal requirement}$$

$$\sum_{i=1}^{N} \left(\frac{O_2 \text{ produced}}{\text{area}} \right)_i (\text{area})_i \geq O_2 \text{ production requirement}$$

protein lower bound

$$\le \sum_{i=1}^{N} \left(\frac{\text{protein produced}}{\text{area}} \right)_i (\text{area})_i$$

$\le$ protein upper bound

carbohydrate lower bound

$$\le \sum_{i=1}^{N} \left(\frac{\text{carbohydrate produced}}{\text{area}} \right)_i (\text{area})_i$$

$\le$ carbohydrate upper bound

lipid lower bound

$$\le \sum_{i=1}^{N} \left(\frac{\text{lipid produced}}{\text{area}} \right)_i (\text{area})_i$$

$\le$ lipid upper bound

where i identifies the crop species and N is the total number of crops being considered. The objective is then to identify the crop mix that minimizes cost while meeting certain requirements for air and water regeneration as well as food production. One could easily modify the above formulation to include additional requirements, such as vitamin and mineral nutritional requirements, or to include additional constraints, such as physical constraints on the crop-growth areas due to rack-size limitations or edge-effect considerations.

This constrained optimization problem can be solved using standard linear programming techniques. We used a SIMPLEX algorithm, coded in FORTRAN on a MicroVax 3200 computer. The algorithm first identifies whether a feasible solution exists, then solves for the optimum solution and determines whether or not the solution is degenerate (i.e., an infinite number of solutions exist).

The optimization method has computational advantages, especially when a large number of crop species or nutritional requirements are being considered. The decision analysis method requires an exhaustive search since the cost of each possible solution must be calculated, whereas the optimization method uses search directions to quickly find the optimum solution. Also, standard methods exist for performing parameter sensitivity analyses for the linear programming formulation. Such analyses would be very useful for performing "what if" studies to investigate the effects of changing costs or productivities of the various crop species.

Results

Table 5 shows the decision analysis output for the baseline case outlined in tables 1–3. For this case we have specified 100% of the requirements for oxygen, carbon dioxide, and carbohydrates to be fulfilled, as well as 40% of those for water, 25% of lipids, and 25% of protein. Results show three crops being selected (lettuce, potatoes, and Y) as the optimum mix, with a total area of 3.0 m^2 and total cost of 2.33. Results also show that in order to supply 100% of the carbohydrate requirement, oxygen, carbon dioxide, water, and protein are oversupplied, and more carbon dioxide is taken up than is necessary. In design optimization terminology, carbohydrates are the active constraint.

Table 6 shows the results of the design optimization technique for the same base set of constraints. Recall that this technique is not limited to equal areas for each species in the crop mix selected. This is reflected in the results, which in this case show three crops being selected (lettuce, Y, and soybeans), with a total area of 2.5 m^2 at a cost of 2.16. Examining the results, we see that the carbohydrate, water, and lipid requirements are active constraints.

The optimization technique can also be used to examine the optimal solution in the case where protein, carbohydrate, and lipid production all become active constraints. This is accomplished by setting the upper and lower bounds on these variables all equal to 100% of the requirements, thus forcing the optimization to choose a crop selection which produces a nutritionally balanced diet (no overproduction of protein, carbohydrates, or lipids). In the baseline case, no feasible solution exists. However, if crop X is substituted for crop Y a solution exists such that exactly 100% of the protein, carbohydrate, and lipid requirements are satisfied. In this example, lettuce, potatoes, and crop X are selected, and carbon dioxide, oxygen, and water requirements are satisfied but are not active constraints.

A study was performed by McDonnell Douglas using decision analysis to determine the optimum crop mix in a CELSS to fulfill nutritional requirements only (ref. 4). Their optimization is based on minimizing crop area (no penalties for power and volume consumption). In their study, it was found that the lowest total area results when no lipid production requirement is placed on the plants. In the baseline case of our study, the lipid requirement to be satisfied by the plants is set to a low level (25%). For this case the lipid requirement is not an active constraint. However, when the requirements for the three nutritional categories are increased to a level of 100%, lipids become the active constraint, which is consistent with the McDonnell Douglas study.

Sensitivities

There are several ways in which sensitivities can be examined. Two approaches are demonstrated below.

From the results of the baseline case, it was determined that carbohydrates were an active constraint. With this in mind, we might like to see how sensitive our answers are to the specified carbohydrate requirement. For example, what happens when the carbohydrate fulfillment level is lowered to 50%? The decision analysis results show a 40% savings in cost and a 15% decrease in crop area using only soybeans and Y. With this new requirements specification, the active constraint shifted to water fulfillment. The design optimization method showed a 38% savings in cost and a 21% decrease in crop area. The active constraints remain carbohydrate and water fulfillment. If these cases were based on real plants, hardware, and mission parameters, this sensitivity analysis would suggest that resupplying a portion of the carbohydrates from Earth might be preferred to requiring the plants to produce the entire requirement, depending on resupply costs.

Another approach to analyzing sensitivities is to examine the effect on the results when plant performance data for a particular species are altered. As an example, the biomass production rate and transpiration rate were varied (doubled and halved) about nominal values. Table 7 lists the results of the two methods in each of these cases. This table shows that certain increases in plant performance parameters result in larger cost savings than others. This method could provide a tool for steering plant research, as well as addressing the balance between transpiration rate and plant biomass production.

Conclusions

1. The design optimization method inherently selects the most optimal crop mix of the two methods considered since it does not require all of the species selected to have equal crop areas. The decision analysis method results are usually within 10% of the cost and total crop area of the design optimization results.

2. The advantages and disadvantages of both methods imply that the two methods are ideal companions to each other. The decision analysis method allows an interactive atmosphere with the user, facilitating experimentation with design specifications. A decision tree displays the cost of all possible crop mixes for the CELSS designers, allowing them to evaluate at a glance the cost of additional variety or preferred (more appetizing) crop species.

The design optimization method has computational advantages, especially when the number of crops being considered or the number of nutritional (or other) constraints becomes large. It also ensures that the last 10% of cost and area savings will be provided by the specified crop mix, and it allows the user to further constrain the optimization problem as needed. A more rigorous sensitivity analysis approach could also be developed using this method.

3. There are limitations to this analysis. A significant limitation of the decision analysis method is the assumption of an equal area for each species in a crop mix. Both methods are limited because they do not allow the plant performance parameters to be simultaneously optimized (the transpiration rate/biomass generation rate trade-off, as well as other variables). No attempt is made to account for the compatibility of crop species if a common air space or nutrient delivery system is planned. Also, the power and volume of the processors required to support a plant system, including environment control, are not accounted for.

References

1. MacElroy, R.; Smernoff, D.; and Rummel, J.: CELSS-Design, Development, and Use of a Ground-Based Plant Growth Module. NASA CP-2479, 1987.

2. Cullingford, H.; and Schwartzkopf, S.: Conceptual Design for a Lunar-Base CELSS. 20th International Conference on Environmental Systems, SAE Paper 901278, July 1990.

3. Gustavino, S.; and Mankamyer, M.: Application of Bioregenerative Subsystems to an ECLSS for a Manned Mars Sprint Mission. 19th International Conference on Environmental Systems, SAE Paper 891504, July 1989.

4. Dyer, L.; and Glover, G.: OPTDES Trade Study of Future CELSS Diet. McDonnell Douglas Space Systems Company Summer Intern Study, September 1990.

5. Dunne, L.: Nutrition Almanac. Nutrition Search, Inc., 1990.

6. PV Module Thermal Control System Trade Study Report. SSF program Office, Reston, VA, Doc. No. SSS-E-39-R5, October 31, 1989.

7. Bilardo, V.: A Generic Trade Study Methodology for the System Analysis of Regenerative Life Support Systems. 21st International Conference on Environmental Systems, SAE Paper 911320, July 1991.

8. Wheeler, R.; and Sager, J.: Carbon Dioxide and Water Exchange Rates by a Wheat Crop in NASA's Biomass Production Chamber: Results from an 86-Day Study (Jan.-Apr. 1989), NASA TM-102788, 1990.

9. Henninger, D.; and Edeen, M.: Regenerative Life Support System (RLSS) Test Bed Performance: Characterization of Plant Performance in a Closed, Controlled Atmosphere. 21st International Conference on Environmental Systems, SAE Paper 911426, July 1991.

10. Tibbitts, T.; Bennett, S.; and Morrow, R.: Environmental and Cultural Considerations for Growth of Potatoes in CELSS. CELSS '89 Workshop, NASA TM-102277, 1989.

11. Tibbitts, T.; Bennett, S.; Morrow, R.; and Bula, R.: Utilization of White Potatoes in CELSS. 1988 COSPAR, NASA CP-10040, 1989.

12. Salisbury, F.; and Bugbee, B.: Plant Productivity in Controlled Environments. HortSci., vol. 23, 1988, p. 293.

13. Salisbury, F.; and Ross, C.: Plant Physiology, 3rd ed. Wadsworth Publishing Company, 1985.

14. McNamee, P.; and Celona, J.: Decision Analysis for the Professional. The Scientific Press, 1987.

15. Hadley, G.: Linear Programming. Addison-Wesley, 1962.

16. Gass, S.: Linear Programming, Methods and Applications. McGraw-Hill, 1969.

Table 1. CELSS specifications input

Species to choose between (up to 5)

1	LETTUCE
2	POTATOES
3	WHEAT
4	Y
5	SOYBEANS

Minumum number of species required	1

Portion of life support requirements fullfilled by plants

% Oxygen	100
% Carbon Dioxide	100
% Water	40
% Lipids	25
% Carbohydrates	100
% Protein	25

Penalties

Cost/kW power	1.44
Cost/m^3 volume	1.56

System parameters

Lighting system efficiency	0.3

Life support requirements for 1 person

Oxygen [Kg/day]	0.84
Carbon Dioxide [Kg/day]	1.00
Water [Kg/day]	31.26
Lipids [gm/day]	105
Carbohydrates [gm/day]	633
Protein [gm/day]	76

Table 2. Plant performance data for model input

Plant species	Trans. rate [Kg/m^2 day]	Biomass growth rate [Kg/m^2 day]	Biomass edible Fraction	Lipids [% Tot. Bio.]	Carbohydrates [% Tot. Bio.]	Protein [% Tot. Bio.]	PPF level [umol/m^2 s]	Lighting photoperiod [hr/day]	Height required [m]
LETTUCE	1.02	0.6	0.8	5	58	22	485	18	0.3
POTATOES	6.41	0.136	0.8	0.5	85	10	725	20	0.11
SOYBEANS	7.7	0.3	0.4	35	20	40	532	12	0.2
WHEAT	9.98	0.4	0.5	2	82	14	534	20	0.6
X	3	0.3	0.7	15	65	5	400	20	0.2
Y	5	0.7	0.5	3	87	2	600	20	0.3

Table 3. Plant performance data for analyses input

Plant species	Transpir. rate* [Kg/m^2]	Biomass trowth* [Kg/m^2]	Lipids produced* [gm/m2]	Carbohydrates produced* [gm/m^2]	Protein produced* [gm/m^2]	CO_2 taken up* [Kg/m^2]	O_2 produced* [Kg/m^2]	Power tequired [kW/m^2]	Total cost* [$/m^2]
LETTUCE	1.02	0.6	24	278.4	105.6	0.88	0.64	0.207	0.7666
POTATOES	6.41	0.136	0.544	92.48	10.88	0.20	0.15	0.344	0.6675
WHEAT	9.98	0.4	4	164	28	0.59	0.43	0.254	1.3013
Y	5	0.6	9	261	6	0.88	0.64	0.285	0.8784
SOYBEANS	7.7	0.3	42	24	48	0.44	0.32	0.152	0.5303

*Production rates are per day.

Table 4. Crop mix cost calculation

Crops chosen	Production per m2/scale factors (X's)												Power	Vol.	Cost	Max
	Water	X	O_2	X	CO_2	X	Lipids	X	Carbo's	X	Protein	X	[kW/m^2]	[m^3]	[per m^2]	X
1	1.0	12.3	0.6	1.3	0.9	1.1	24.0	1.1	278.4	2.3	105.6	0.2	0.2	0.3	0.767	12.3
2	6.4	2.0	0.1	5.8	0.2	5.0	0.5	48.3	92.5	6.8	10.9	1.7	0.3	0.1	0.668	48.3
3	10.0	1.3	0.4	2.0	0.6	1.7	4.0	6.6	164.0	3.9	28.0	0.7	0.3	0.6	1.301	6.6
4	5.0	2.5	0.6	1.3	0.9	1.1	9.0	2.9	261.0	2.4	6.0	3.2	0.3	0.3	0.878	3.2
5	7.7	1.6	0.3	2.6	0.4	2.3	42.0	0.6	24.0	26.4	48.0	0.4	0.2	0.2	0.530	26.4
1 2	3.7	3.4	0.4	2.1	0.5	1.9	12.3	2.1	185.4	3.4	58.2	0.3	0.3	0.2	0.717	3.4
1 3.	5.5	2.3	0.5	1.6	0.7	1.4	14.0	1.9	221.2	2.9	66.8	0.3	0.2	0.5	1.034	2.9
1 4	3.0	4.2	0.6	1.3	0.9	1.1	16.5	1.6	269.7	2.3	55.8	0.3	0.2	0.3	0.822	4.2
1 5	4.4	2.9	0.5	1.7	0.7	1.5	33.0	0.8	151.2	4.2	76.8	0.2	0.2	0.3	0.648	4.2
2 3	8.2	1.5	0.3	2.9	0.4	2.5	2.3	11.6	128.2	4.9	19.4	1.0	0.3	0.4	0.984	11.6
2 4	5.7	2.2	0.4	2.1	0.5	1.9	4.8	5.5	176.7	3.6	8.4	2.3	0.3	0.2	0.773	5.5
2 5	7.1	1.8	0.2	3.6	0.3	3.1	21.3	1.2	58.2	10.9	29.4	0.6	0.2	0.2	0.599	10.9
3 4	7.5	1.7	0.5	1.6	0.7	1.4	6.5	4.0	212.5	3.0	17.0	1.1	0.3	0.5	1.090	4.0
3 5	8.8	1.4	0.4	2.2	0.5	1.9	23.0	1.1	94.0	6.7	38.0	0.5	0.2	0.4	0.916	6.7
4 5	6.4	2.0	0.5	1.7	0.7	1.5	25.5	1.0	142.5	4.4	27.0	0.7	0.2	0.3	0.704	4.4
1 2 3	5.8	2.2	0.4	2.1	0.6	1.8	9.5	2.8	178.3	3.6	48.2	0.4	0.3	0.3	0.912	3.6
1 3 4	5.3	2.3	0.6	1.5	0.8	1.3	12.3	2.1	234.5	2.7	46.5	0.4	0.2	0.4	0.982	2.7
1 4 5	4.6	2.7	0.5	1.6	0.7	1.4	25.0	1.1	187.8	3.4	53.2	0.4	0.2	0.3	0.725	3.4
1 2 5	5.0	2.5	0.4	2.3	0.5	2.0	22.2	1.2	131.6	4.8	54.8	0.3	0.2	0.2	0.655	4.8
1 3 5	6.2	2.0	0.5	1.8	0.6	1.6	23.3	1.1	155.5	4.1	60.5	0.3	0.2	0.4	0.866	4.1
1 2 4	4.1	3.0	0.5	1.8	0.7	1.5	11.2	2.3	210.6	3.0	40.8	0.5	0.3	0.2	0.771	3.0
2 3 4	7.1	1.8	0.4	2.1	0.6	1.8	4.5	5.8	172.5	3.7	15.0	1.3	0.3	0.3	0.949	5.8
2 4 5	6.4	2.0	0.4	2.3	0.5	2.0	17.2	1.5	125.8	5.0	21.6	0.9	0.3	0.2	0.692	5.0
2 3 5	8.0	1.6	0.3	2.8	0.4	2.4	15.5	1.7	93.5	6.8	29.0	0.7	0.2	0.3	0.833	6.8
3 4 5	7.6	1.7	0.5	1.8	0.6	1.6	18.3	1.4	149.7	4.2	27.3	0.7	0.2	0.4	0.903	4.2
1 2 3 4	5.6	2.2	0.5	1.8	0.6	1.6	9.4	2.8	199.0	3.2	37.6	0.5	0.3	0.3	0.903	3.2
1 2 3 5	6.3	2.0	0.4	2.2	0.5	1.9	17.6	1.5	139.7	4.5	48.1	0.4	0.2	0.3	0.816	4.5
1 2 4 5	5.0	2.5	0.4	1.9	0.6	1.7	18.9	1.4	164.0	3.9	42.6	0.4	0.2	0.2	0.711	3.9
1 3 4 5	5.9	2.1	0.5	1.7	0.7	1.4	19.8	1.3	181.9	3.5	46.9	0.4	0.2	0.4	0.869	3.5
2 3 4 5	7.3	1.7	0.4	2.2	0.5	1.9	13.9	1.9	135.4	4.7	23.2	0.8	0.3	0.3	0.844	4.7
1 2 3 4 5	6.0	2.1	0.4	1.9	0.6	1.7	15.9	1.7	164.0	3.9	39.7	0.5	0.2	0.3	0.829	3.9

Table 5. Decision analysis baseline results

Total crop area [m^2]	3.0
Number of plant species	3
Area planted per specie [m^2]	1.0
Total power required [kW]	0.84
Total volume required [m^3]	1.40
Total cost of plants	2.33

Species selected

1	LETTUCE
2	POTATOES
3	Y
4	
5	

Life support requirements by output crop mix

% Oxygen	171
% Carbon dioxide	231
% Water	74
% Lipids	58
% Carbohydrates	100
% Protein	202

Table 6. Design optimization baseline results

Total cost	=	2.1595		
Total area	=	2.5004	m^2	
Area of crop #1 (Lettuce)	=	0.0584	m^2	
Area of crop #2 (Potatoes)	=	0.0000	m^2	
Area of crop #3 (Wheat)	=	0.0000	m^2	
Area of crop #4 (Y)	=	2.3549	m^2	
Area of crop #5 (Soybeans)	=	0.0870	m^2	
CO_2 removed	=	2.1621	kg/day	(216.21 % of human reqt.)
O_2 produced	=	1.5724	kg/day	(187.19 % of human reqt.)
H_2O processed	=	12.5040	kg/day	(40.00 % of human reqt.)
Protein produced	=	24.48	g/day	(32.21 % of human reqt.)
Carbohydrate produced	=	633.00	g/day	(100.00 % of human reqt.)
Lipid produced	=	26.25	g/day	(25.00 % of human reqt.)

Table 7. Parameter sensitivity analysis results

Crop Y		Transpiration rate [kg/m^2 d] 2.5	5.0 (nominal)	10.0
Biomass generation rate [kg/m^2 d]	0.35	DA cost: 2.45 area: 3.4 m^2 species: L,P OPT cost: 2.36 area: 3.50 m^2 species: L,S	DA cost: 2.45 area: 3.4 m^2 species: L,P OPT cost: 2.36 area: 3.50 m^2 species: L,S	DA cost: 2.42 area: 2.9 m^2 species: L,Y OPT cost: 2.24 area: 2.76 m^2 species: L,Y
	0.70 (nominal)	DA cost: 2.42 area: 3.3 m^2 species: L,Y,S OPT cost: 2.28 area: 2.98 m^2 species: Y,S	DA cost: 2.27 area: 3.1 m^2 species: L,Y,S OPT cost: 1.96 area: 2.34 m^2 species: Y,S	DA cost: 1.87 area: 2.3 m^2 species: L,Y OPT cost: 1.79 area: 2.17 m^2 species: L,Y
	1.40	DA cost: 1.73 area: 2.5 m^2 species: Y,S OPT cost: 1.56 area: 2.29 m^2 species: Y,S	DA cost: 1.41 area: 2.0 m^2 species: Y,S OPT cost: 1.40 area: 1.97 m^2 species: Y,S	DA cost: 1.19 area: 1.4 m^2 species: Y OPT cost: 1.06 area: 1.32 m^2 species: Y,S

LEGEND:

P = potato

L = lettuce

W = wheat

S = soybeans

Y = Y

DA = results from decision analysis

OPT = results from design optimization

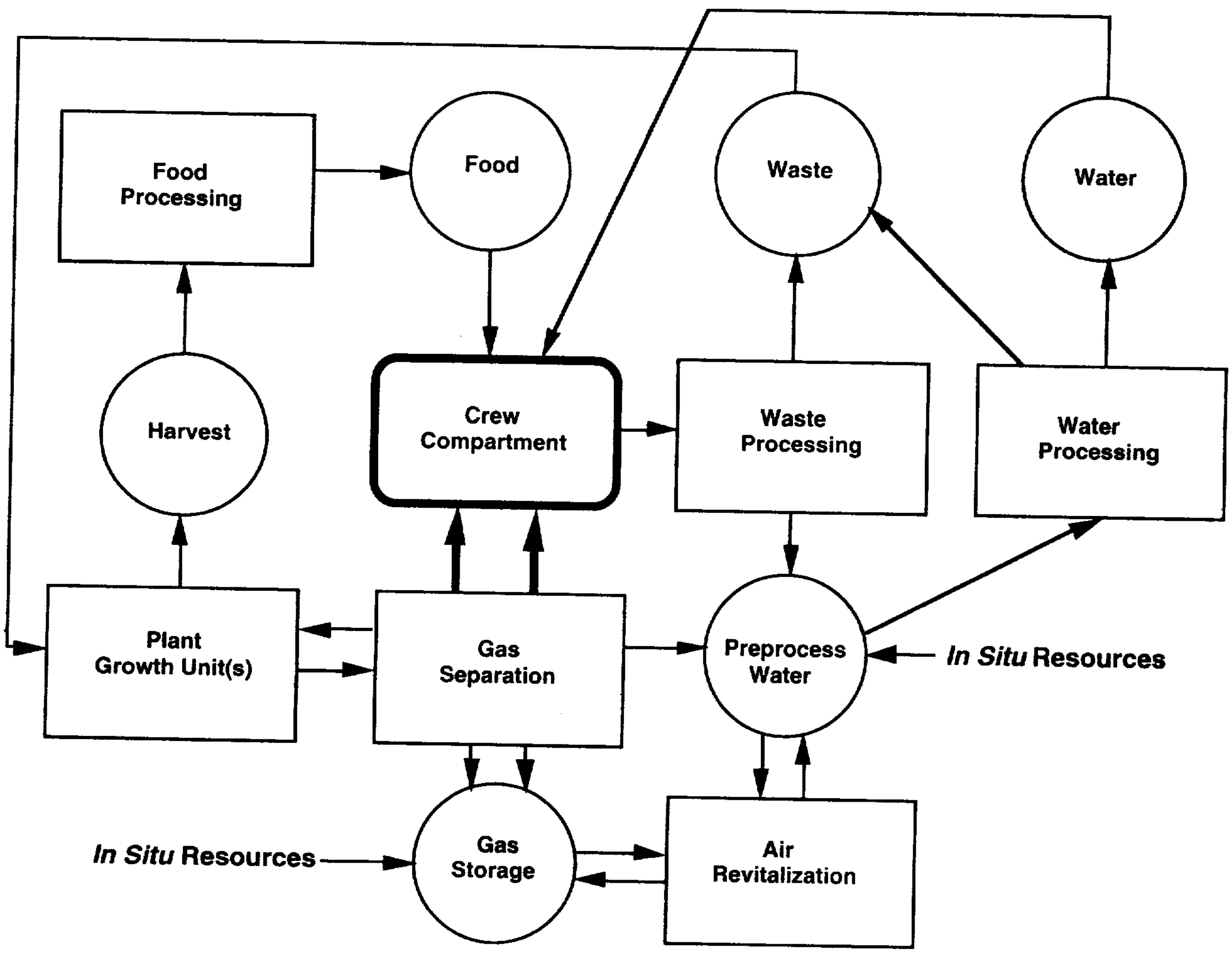

Figure 1. Conceptual design for a Controlled Ecological Life Support System.

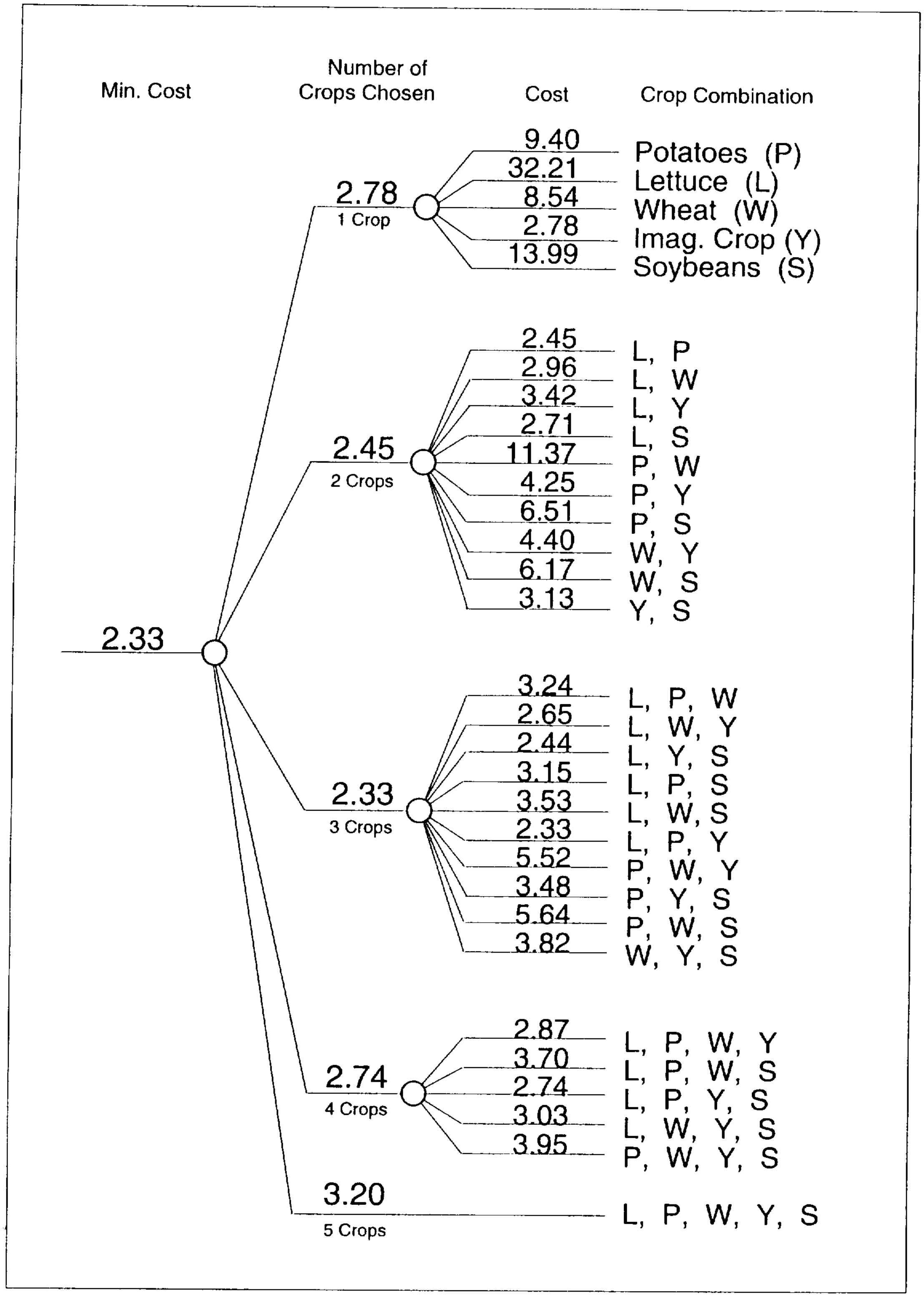

Figure 2. Decision Tree.

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13. ABSTRACT ***(Maximum 200 words)***

A Controlled Ecological Life Support System (CELSS) utilizes a plant's natural ability to regenerate air and water while being grown as a food source in a closed life support system. Current plant research is directed toward obtaining quantitative empirical data on the regenerative ability of each species of plant and the system volume and power requirements. Two techniques were adapted to optimize crop species selection while at the same time minimizing the system volume and power requirements. Each allows the level of life support supplied by the plants to be selected, as well as other system parameters. The first technique uses decision analysis in the form of a spreadsheet. The second method, which is used as a comparison with and validation of the first, utilizes standard design optimization techniques. Simple models of plant processes are used in the development of these methods.

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