Application of Supply Chain Optimization and Protocol Environment Architecture to ALS Modeling and Visualization

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ABSTRACT

A significant amount of software has been developed to model the advanced life support aspects of a Mars surface habitat. Models, such as the BIO-Plex Baseline Simulation Model (Finn, 1999), have been useful in studying advanced life support systems. These models have been used to conduct trade study comparisons to determine which Advanced Life Support (ALS) technologies should currently be used in a habitat design. However, the present models and approaches require significant overhead to exchange one technology for another mostly because the models are mission centric and assume either that the habitat will be stationary or that the life of the habitat will be same as the mission duration. In other words, these models lack the desired level of modularity necessary to quickly complete multiple trade studies of different missions as the habitat evolves from mission to mission.

The XML-based (Extensible Markup Language) Supply Chain Optimization and Protocol Environment (SCOPE) architecture provides a mechanism to achieve the required level of plug-and-play capability. SCOPE has previously been used to study policy interactions within several different supply chain networks (Orcun *et. al*). In this work, the SCOPE methodology is applied to a Mars surface habitat simulation without optimization. This results in a network of components such as crew members, storage, and ALS technologies. Each component is represented as a self-contained node in the network. For each node, there is an XML description of the required material inputs and outputs. The simulation engine interprets each description to form the entire network and to properly handle the interactions between each node in the network.

In this work we will present a preliminary implementation of this architecture for habitat analysis and three case studies that demonstrate the challenges of habitat evolution. We also describe a virtual environment that visually displays the results from the simulation architecture.

INTRODUCTION

Several attempts have been made to model and simulate advanced life support systems that could exist on potential Lunar (Drysdale, 1994) and Mars Surface Habitats (Fleisher *et al*., 1999; Rodriguez *et al*., 1999). For Mars Surface Habitats, in particular, one issue that is not usually considered is that of habitat evolution between missions. This is understandable given the complexity of advanced life support systems (Aydogan *et al*., 2003) because adding in the concept of designing a habitat of a 15 to 30 year lifespan adds an additional layer of complexity. In this paper we detail a simulation tool that was developed to simulate a Mars Surface Habitat rapidly. This simulation tool is based off of the Supply Chain Optimization and Protocol Environment (SCOPE) architecture. Furthermore, we propose an XML (Extensible Markup Language, further information on XML can be found at http://www.xml.org/) based language that will be used to describe the topology of the habitat. It will also be used to define which models will be executed at any given point during the simulation. In addition, the language will be used to define how information is transferred throughout the entire architecture. This includes both specifying what information from the habitat components are needed for each model to be executed and what information is generated by each model to in turn be used by other habitat components. This language constitutes the heart of the plug and play capability of the architecture. Using this language, a user can quickly swap in and out technologies in order to conduct the trade studies necessary to design a surface habitat that evolves over time in the proposed environment. In addition, we present three case studies that show the difference between considering habitat evolution and not considering habitat evolution. We also developed a real-time high quality interactive virtual simulation environment to visually study these different scenarios. We use this environment to demonstrate how visualization can be utilized effectively in presenting the habitat characteristics of these three case studies.

XML HABITAT DESCRIPTION

SCOPE methodology views a habitat as a directed graph whose nodes represent facilities such as crew, recovery technologies, etc., while arcs represent both information and material flows. Differentiating between material flow and information flow provides a rich environment where one can represent advanced control strategies, simulate different information sharing and visibility conditions (e.g. between local and central or supervisory controllers), and model delays in material flow. In this way, we can incorporate specific decision models into the different nodes, as opposed to the relatively simple decision rules observed in most systems dynamics work. At the same time, it is possible observe the effects of these advanced decision models on system behavior (an example for supply chain analysis can be found in Orcun *et. al*).

To achieve a robust scalable plug-and-play capability an XML based language is developed to describe the habitat topology in terms of both material and information flows, the roles of each node and their data requirements, and the mapping of the nodes that will be executed in each pass. Information and material flow between the nodes of the habitat are handled through property visibility in a manner analogous to message boards.

```
<?xml version="1.0" ?>
<HABITAT>
<HORIZON>35</HORIZON>

  <NODES>
   <NODE>
...
   </NODE>

   <NODE>
...
   </NODE>
  </NODES>

  <ARCS>
     <ARC>
 ...
     </ARC>

    <ARC>
 ...
     </ARC>
  </ARCS>

</HABITAT>
```

Listing 1: XML Language Skeleton

The language, as shown in Listing 1, is basically two main constructs, one for node specification and one for flow specification. The node specification consists of the name of the node, the execution window of the node, the properties it needs to track, and the agents it will execute. A node, as shown in Listing 2 may consist of multiple agents such as a local control unit and a processing unit.

```
<NODE id="18">
         <NAME>Water Recovery</NAME>
          <TYPE>Production</TYPE>
          <WINDOW>
            <EXECUTION>1</EXECUTION>
          </WINDOW>
          <OBSERVE_PROPERTY>
            <NAME>X</NAME>
            <NAME>Y</NAME>
          </OBSERVE_PROPERTY>

          <AGENT>
...
          </AGENT>
          <AGENT>
...
          </AGENT>

</NODE>
```

Listing 2: Node Construct

As shown in Listing 3, each agent in a node has several requirements such as a name and an execution characteristic. The execution characteristic determines when an agent is called (e.g. at every iteration or at start-up, etc.). For a habitat description, most agents will be called during every iteration, e.g. daily. Also, the language needs to know the application to call (i.e. EXCEL in this case), the path to the file, and the name of the file. Furthermore, it is necessary to list the command that executes the model (i.e. the appropriate VBA macro function). Also, in order for the controller to know what information to provide, the agent must list the input data that the model needs. Similarly, the information that the model provides as output must be listed as well. As shown in Listing 3, the input requirements will be listed in the import tag, and the output information will be listed in the export tag.

```
<AGENT>
           <NAME>Clean Water</NAME>
           <APPLICATION>
            <EXECUTION>Iteration</EXECUTION>
            <TYPE>EXCEL</TYPE>
            <PATH>foo</PATH>
            <NAME>foo.xls</NAME>
            <COMMAND>foo</COMMAND>
           </APPLICATION>
           <IMPORT>
            <PROPERTY>
...
            </PROPERTY>
           </IMPORT>


           <EXPORT>
            <PROPERTY>
...
            </PROPERTY>
           </EXPORT>
</AGENT>
```

Listing 3: Agent Construct

The property tag is used to specify both where the model expects to find its inputs and where to place its outputs. In this case, this would be where the inputs and outputs are placed in the associated Excel file. Property specification, as shown in Listing 4, consists of the property name, the table and column where it is located, the layout of the table, and whether it has a header or not. Also listed in the specification is the type of table database (e.g. Excel sheet) and the file it is located in (in this case an Excel file). Finally, it is conceivable that information from previous time periods (e.g. days) may need to be a property. Therefore, there is both a start and an end property which specifies how many time periods either before or after the current one that information should be recorded. For example, for a crewmember, it might be important to know the food and water input for the last several days. If a crewmember were not getting enough food for several days, then the crewmember might only be able to function at a reduced capacity or even die. Obviously, this would depend on the level of detail within the crewmember model.

```
<PROPERTY>
   <NAME>flow</NAME>
   <TABLE_NAME>foo</TABLE_NAME>
   <TABLE_COLUMN>1</TABLE_COLUMN>
   <TABLE_HEADER>False</TABLE_HEADER>
   <TABLE_LAYOUT>Portrait</TABLE_LAYOUT>
   <TABLE_INDEX_FORMAT>Relative</TABLE_INDEX_FORMAT>
   <TABLE_TYPE>EXCEL</TABLE_TYPE>
   <DB_NAME>foo.xls</DB_NAME>
   <RELATIVE_START>0</RELATIVE_START>
   <RELATIVE_END>0</RELATIVE_END>
</PROPERTY>
```

Listing 4: Property Construct

The final construct, depicted in Listing 5, is used to specify the connectivity (flows). It requires the start and end nodes, the type of the flow (material or information), and the list of visible properties on this arc. This visibility list provides the message board logic in which the shelf-life of information can be specified.

```
<ARC>
   <FROM>crew</FROM>
    <TO>Water Recovery</TO>
    <TYPE>Material</TYPE>
     <VISIBLE>
      <PROPERTY>
       <NAME>grey water</NAME>
       <ABSOLUTE_START>0</ABSOLUTE_START>
       <RELATIVE_END>0</RELATIVE_END>
      </PROPERTY>
     </VISIBLE>
 </ARC>
```

Listing 5: Arc Construct

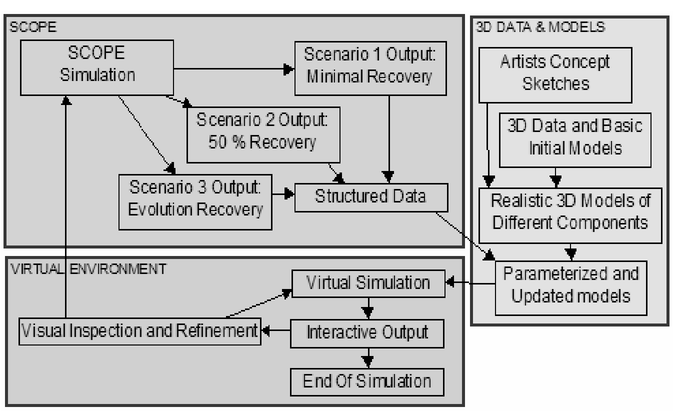

Figure 1: Architecture layout of SCOPE, 3D Data & Models, and Virtual Simulation Environment

VIRTUAL SIMULATION ENVIRONMENT

Figure 1 shows the architecture layout that integrates the SCOPE-Based Simulation Tool, the 3D data and realistic models, and the interactive virtual simulation environment. The toolsets we used for modeling are Discreet 3DS Max 7.0, Adobe Photoshop CS, and Curious Labs Poser.

MARTIAN TERRAIN

The Martian terrain contains two parts - geometry and texture. Since we did not have a digital elevation model of the terrain, we created the polygonal mesh in 3DS Max and edited the surface height map to visually match some of the Martian images. Since we required high resolution texture images, we used a few of the images captured by the Mars rovers (NASA/JPL) and blended them together to form a relatively largely detailed high resolution texture.

Most of the objects were created based on the illustrations provided by concept artists (See Surface Habitat in Additional Sources). These include the capsule module, the habitat living space, the gas tanks, and the crop cabin. The rest of the objects, such as the nuclear reactors and the solar panels, were modeled based on reference pictures. Most of the textures were created from scratch using Adobe Photoshop. All of the 3D models are sized based on either real world counterparts or on calculations from the simulation. Within the virtual environment the 3D models are at a 1:1 scale with their real world or calculated counterparts. The layout of all the components for each of the scenarios is based on the requirements that result from the SCOPE-based simulation of each scenario. Output from the SCOPE-based simulation tool for different components is stored in a pre-defined structured table. This structured information is then used to update and modify different components in the visualization simulation system to visually display different scenarios.

Each scene is primarily composed of four parts. They are: a) Crew cabin – habitat for astronauts, b) Crop cabin, c) Energy generators – nuclear reactors and solar panels, and d) Storage containers for food, water, grey water, waste, and gases. Each of these cabins and storage containers are connected by transportation pipes and/or walk-through tunnels as required. The pipes and tunnels are perfectly aligned to form a transportation network. The 3D models of these four parts each contain within them multiple components and items as detailed below.

CREW CABIN – HABITAT FOR ASTRONAUTS

From a modeling perspective the crew cabin consists of two components. They are an outside unit and an inner space unit. The outside unit is the exterior structure of the crew cabin. As shown in Figure 2, the inner space unit, which sits inside the outside capsule, represents the two story tall interior structure. The first floor contains a kitchen, a shower room, and a work area. The kitchen has a refrigerator, a laundry machine, closets, a water sink, and a garbage bin. The second floor contains a living quarters and a compact bedroom for each of the astronauts. The living quarters contains furniture such as desks, chairs, and a table. In addition green plants, a water filter, and a CO_2 scrubber are included in the crew cabin. These are meant to represent life-support equipment within the habitat. Detailed virtual human models were placed in the living room to demonstrate the dimensions and environment of the living space.

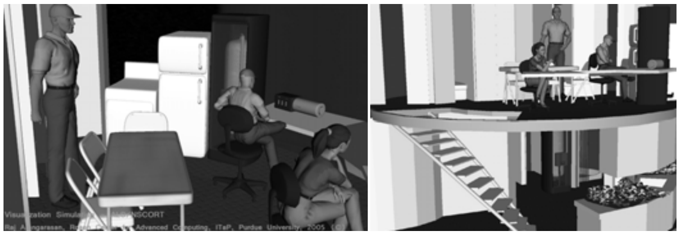

Figure 2: Crew Cabin – Habitat for Astronauts

CROP CABINS

Crop cabins are made of inflatable shells. Each crop cabin has two layers - the outer layer depicts a rubber inflatable shell and the inner one represents a transparent layer that contains the elements within the crop cabin. Both layers are perfectly aligned with each other and are connected by an oval-shaped door. The distinction between the two layers is really only important for the graphical implementation of the inflatable shell. The outer later will show what is on the outside of the shell, while the inner layer will contain and show all of the graphical elements that are within the shell. As shown in Figure 3, each crop cabin contains a variety of crops that are planted on two levels of trays. Two detailed virtual human models are also placed in this cabin to demonstrate the green house's relative size, working environment, and accessibility.

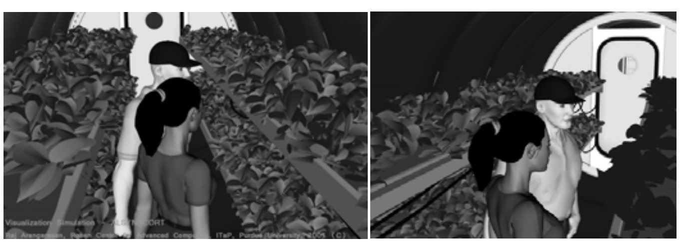

Figure 3: Inside Crop Cabin

STORAGE TANKS AND CABINS (FOOD, GASES, AND WASTE)

In all of the scenarios, there are three tanks located outside of the crew cabin. The tank sizes can be easily changed to fit different amount of gases. These tanks, as shown in Figure 4, represent storage for O_2, N_2, and CO_2. Though not visible in Figure 4, the tanks are labeled with color coded labels in order to indicate the contents of each tank. Furthermore, each of the tanks contains a detailed gauge that shows the stored amount of its contents. The gauges are illustrated in the right image in Figure 4. The gauge amounts change for different scenarios depending on the requirements specified by the SCOPE-based simulation engine. There is also piping that connects these tanks to the rest of the habitat.

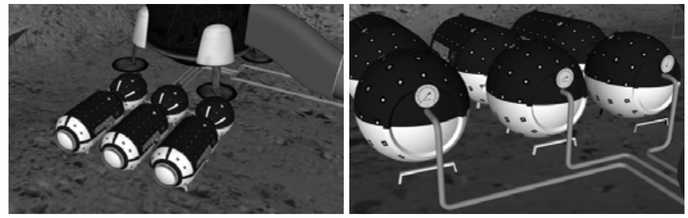

Figure 4: Gas (O2, N2, CO2) Storage Tanks

In addition to the storage tanks, there is also at least one storage module in each scenario. These modules were placed around the crew cabin and are connected to it via the network of walkthrough tunnels. These additional capsule modules are the same shape as the crew cabin, but they are instead sized based on the assumption that one storage module would have a volume equivalent to that of one shuttle payload. Three kinds of labels, such as "Food", "H_2O", and "Waste Recycle/Treatment" logos, can be printed on top of the capsule so that users know what each module contains. Along with the contents labels, additional labels can be placed on top of the tanks to bring realism to the scene.

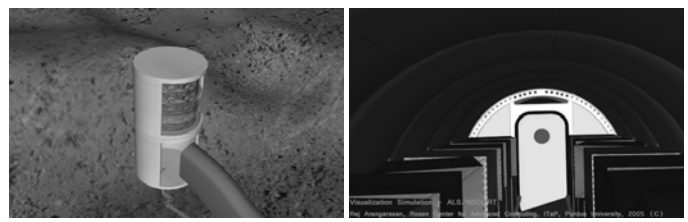

Figure 5: Food, Water and Storage Cabin Interiors

Figure 5 shows the inside of the food container capsule module. This food container contains multiple sections. The upper half is divided into two cylindrical cores. The outer core contains clean water and the inner core contains solid food. The outer core of water acts as an additional shield to protect food from radiation and other environmental factors. The lower half of the capsule module is used to store grey water. In one scenario, one of the inflatable cabins is used for additional storage. Two levels of boxes were put in this inflatable cabin to represent this storage. The boxes represent a placeholder for the type of storage container that would actually be used. Clearly, the actual container would vary depending on what is stored there (e.g. waste vs. food).

ENERGY GENERATION (NUCLEAR REACTOR AND SOLAR PANELS)

In each of the scenarios (see Case Studies), energy is primarily generated using nuclear reactor(s) and solar panels. Usually, the solar panels are used to generate additional power when adding an additional nuclear reactor would be too costly. In our model, we used SP100 nuclear reactors. The nuclear reactors are represented as being buried under the ground to protect the reactor and minimize any radiation. A matrix of solar panels was placed adjacent to the crew-cabin. For the first scenario, the solar panels are there for testing and supplemental purposes. For the last two scenarios, the number of solar panels is based on the energy requirements generated from the SCOPE-based simulation engine. This is only a preliminary consideration of the energy requirements of a surface habitat. In terms of the visualization, issues such as the location of heat rejection radiators (which would affect the power requirements) have not been considered in this work. Visualization choices that impact material and energy costs will be considered in a future work.

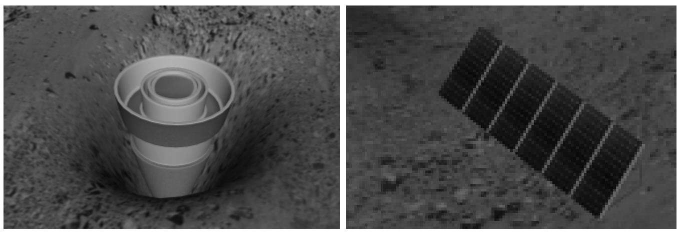

Figure 6: Energy Generation – SP100 nuclear reactor and Solar Panels

Once the 3D models were completed, they were converted into an Open Scene Graph file format for import into a custom-built virtual reality simulation application. Polygonal optimization, texture compression, and advanced shading mechanisms were used to achieve interactive frame rates (Foley, *et al*., 1997).

MODEL OVERVIEW

The habitat simulation engine was developed using Microsoft Excel in conjunction with Microsoft Visual Basic (VBA). It is made up of several different Excel workbooks each with several VBA Macros. The most important workbook is the controller workbook which runs the simulation. Based on the interface, the controller workbook has an overall macro that runs the simulation for a specified number of days. This is done by first calling macros that initialize all of the other system workbooks (e.g. Crew Cabin, Oxygen Storage, Human, etc.). Then the overall macro loops through all of the days. Each of the system workbooks is then called through a macro at each period, a day in this case. When the system workbook is called, the controller workbook provides to the system workbook information that the system workbook needs. Each system workbook then runs its own macros that make use of the information that was provided to it from the controller workbook. Once those macros are completed, the controller workbook then takes certain information from the just updated system workbook. This information is then used as input information for other system workbooks that will be called later in the simulation. This structure allows for a flexible architecture because each system workbook does not need to know about the other system workbooks because they all rely on the controller workbook for any necessary information. This clear decoupling and the XML language designed to describe the topology makes it possible to rapidly substitute even dissimilar technologies (modeled in two separate self-contained workbooks) by minimizing if not eliminating the impact to the rest of the system workbooks. Furthermore, this decoupling provides us a device for a technology independent execution logic which starts from the demand nodes, e.g. crew, and proceeds towards supplier nodes where we can use the SCOPE controller workbook to handle the interactions. The controller workbook is an implementation of a dynamic simulation concept (also known as integrator) which eliminates the need to simultaneously solve all of the system models. This is provided that the chosen time step is small relative to the duration of the simulation and that the appropriate level of abstraction or detail is utilized in models described in each self-contained system workbook relative to this time step (one iteration of the controller).

For example, when the O_2 Storage system workbook is called for a particular day, it is provided with the change in O_2 throughout the entire habitat. The controller workbook would have this information because it keeps a running total of the O_2 requirements from other system workbooks that would have been previously called for that day. For example, each of the 6 crew member workbooks would have been previously called for that day. They would each have an O_2 requirement that the controller workbook would store and then provide to the O_2 Storage workbook.

The O_2 Storage system workbook then takes that information and uses it within its own workbook. In this case, the O_2 Storage Macro would simply reduce the current amount of O_2 in storage by what is required by the habitat for that day. Once the macro is complete the controller workbook takes any important output information. In this case, the output information would be how much O_2 is left in the storage container. The controller workbook then takes this information and records it for the corresponding day. Subsequent system workbooks may require the information that was just obtained.

MODELS

In this section we will describe the models used in the demonstration case studies which are described further in the paper. The purpose of these models and the case studies is not to propose an optimal solution or recommendation. On the contrary, the scenarios used in these case studies are crafted to emphasize the intended messages we wish to deliver in this paper which are 1) demonstrate the flexibility and robustness of the environment, 2) show the significance of evolution and lifecycle analysis, and 3) illustrate the value of using visualization in presenting ALS characteristics. However, the models described below are derived from the biological and physical characteristics and represented in self-contained workbooks so that they can be repeatedly utilized in different scenarios hence creating a model toolbox. For more detail about models detailed below, see Appendix A. For more detail about the assumptions that were made, see Appendix B.

Crew Member Model

The Bio-Plex human model was used for all 6 crew members (Finn, 1999). For each crew member, there is a mass both for what goes in and out of the body and for what is used but is not ingested (e.g. water for hygiene and clothes). The stoichiometric reaction from Volk and Rummel is used to govern what the inputs and outputs should be for each crewmember (Volk and Rummel, 1987). Nine other equations are solved simultaneously in order to obtain values for all of the input and output terms. They include species balances on carbon, hydrogen, oxygen, and nitrogen. They also include urine and feces solid ratio equations from Volk and Rummel (Volk and Rummel, 1987). Food is assumed to be in the form of Proteins, Carbohydrates, and Fats for simplicity. The Bio-Plex equations that govern how much wheat, rice, peanuts, and soy are ingested are translated into ingested Protein, Carbohydrates, and Fat (Finn, 1999). The three ingestion amounts are then used as the last three equations that need to be solved. In other words, these three equations will directly specify the totals for Proteins, Carbohydrates, and Fats (e.g. $n_{Protein}$ = constant). See Appendix A for more detail about how the food consumption totals and the waste generation totals are calculated. Below are details about some of the specific models used in the case studies discussed below.

Crop Growth Model

The Bio-Plex crop models were used as a template for the generic crop model (Finn, 1999). See Appendix A for a description of the equations used in the BIO-Plex model. This was used so that a crop schedule would not have to be devised. See Table 1 for the parameters for the generic crop (See the work of Aydogan, *et al*. (2004) for an example of a generic crop). When terms could not be derived, values that were listed for rice were assumed to be acceptable.

Crew and Crop Cabin Model

The crew cabin and crop cabin atmospheric partial pressure upper and lower bounds were obtained from Table 4.1.1 in the BVAD (Hanford, 2004A). The system maintains the O_2, CO_2, N_2, and water vapor levels inside the crew cabin and the crop cabin by ensuring that they remain within the given upper and lower bounds as specified in Table 4.1.1 of the BVAD (Hanford, 2004A). Furthermore, a small amount of leakage is assumed to occur at the end of each day (refer to Appendix B for values assumed).

Water Recovery Model

For all of the case studies, very basic water recovery models were used. In this paper, it is assumed that water recovery can come from two sources. First, it is assumed that any excess water vapor (above the partial pressure above the upper bound from Table 4.1.1 in the BVAD (Hanford, 2004A)) the crew or crop cabin can be completely condensed into potable water. Second, certain scenarios, discussed below, will allow for the recovery of some fraction of the grey water. The rest of the grey water would then be considered untreatable waste. The fraction of the grey water that can be recovered must be specified in the scenario

Table 1: Generic Crop Parameter Values

Parameter	Value (Units)
Amax	0.93
Qmin	0.01
c	0.68
ta	12 (days)
tq	33 (days)
tm	100 (days)
area	150 (m^2)
ppf	1200
h	20 (hours)
Edible Protein Ratio	0.484
Edible Carbohydrate Ratio	0.236
Inedible Protein Ratio	0.5128
Inedible Fiber Ratio	0.3755
Edible Mass Fraction	0.36
Edible Water Mass Fraction	0.1356
Inedible Water Mass Fraction	0.5

CO_2 Generation Model

For the second and third case studies a simple CO_2 generation system has been put into place. When there is excess O_2, waste (inedible plant material and feces) is combusted to form CO_2. The user must specify both the carbon content of the waste and what fraction of the carbon can be recovered as CO_2. For this model, it is assumed that the carbon content of waste is fifty percent and that only half of the carbon can be recovered as CO_2.

Power Generation

For daily energy consumption, two sources were used. For everything but crops, the NASA FY-04 Metric Document was used to provide a ballpark estimate of the energy requirements of the habitat (Hanford, 2004B). For the crops, Table 4.2.2 of the BVAD was used to calculate the energy consumption (Hanford, 2004A). Finally, for simplicity the cooling requirements are assumed to be equal to the input energy requirements. In other words any energy put into the system must be removed in order to maintain the desired temperature.

CASE STUDIES

We conducted three case studies in order to understand the difference between a Mars Scenario that represents a first mission and a Mars Scenario that represents a second mission. The first case study is a basic camping trip scenario that represents a simple first mission. The second case study is a fifty percent closure scenario that also represents a first mission to Mars. The final case study is also a fifty percent closure scenario, but it assumes that the mission from the first case study occurred previously. In each of these studies, the simulation tool is used to determine the required amount of material (food, water, O_2, etc) that must be shipped from Earth in order to satisfy the requirements of the crewmembers and any crops that may be growing. It will also be used to estimate the energy requirements for each case study. Rather than generating recommendations for the optimal design of a Mars base ALS system, the intention of the case studies presented in this section is to demonstrate the simulation environment described above, the differences between going to an empty Mars versus an existing Mars base that is evolving, and how to utilize advanced visualization to represent the characteristics of different ALS designs.

MARS MINIMAL CLOSURE SCENARIO

For the first case study, we assumed 6 crew members for 750 days. To some extent the duration of this case study was set arbitrarily to be 30 days more than Mars surface mission period (2-years). This was to allow for some contingency. In this scenario, there are two small sources of recovery. The first source is excess water vapor that is condensed and directly sent to potable water storage. The second, is that there is a small amount of crops that are grown and harvested during the course of the mission to represent experimental plant growth. Note that the crops are assumed to be there for testing purposes. The crew does not rely on them to supplement the diet, generate O_2, or remove CO_2. As the crops grow they use some CO_2, provide some O_2, and generate some food. A generic crop is assumed that provides average amounts of proteins, carbohydrates, and fats. Otherwise, the rest of the required food, water, and O_2 are shipped from Earth.

MARS FIFTY PERCENT CLOSURE SCENARIO

For the second case study, we again assumed a 750 day mission with 6 crew members. The key difference from the previous scenario is that there is now a goal of fifty percent closure. Note, that the fifty percent closure scenario is based off of the idea that it is necessary to grow half of the food required by the crew. In this scenario, however, the fifty percent closure refers to the amount of food that is grown to satisfy the crew's nutritional requirements, the amount of waste water that is recovered, and the amount of waste combusted to form CO_2. In this case, the fraction of grey water that can be recovered has been assumed to be 0.5 in order to be consistent with the fifty percent closure assumption for this scenario. In addition, the carbon fraction of the waste was assumed to be roughly 0.5 (because the waste would be high in the inedible biomass and average carbon content of biomass can be estimated as approximately 0.5 from Table 4.2.8 in BVAD (Hanford, 2004A)) and it was assumed that only half of that carbon can be recovered (to be consistent with the fifty percent closure scenario).

In this mission, crops are used to grow food, and to provide oxygen for the crew. The same generic crop listed above is used in this mission. The generic crop is assumed to have to grow for 100 days before it can be harvested. There is then a 30 day period before the crop area can be used again. To simplify things, it was assumed that the entire crop area is planted all at one time and later harvested all at one time. Therefore, the entire plant area is at the same stage of growth. It is also assumed that any food that comes from harvested crops does not go bad before it is used, i.e. infinite shelf-life. Finally, feces and inedible plant material are combusted in order to form additional CO_2 to meet the requirements of the crops.

MARS EVOLUTION CLOSURE SCENARIO

This scenario uses most of the same assumptions as in the previous scenario. In other words, it is again a 750 day scenario for 6 crew members with the amount of closure similar to what was discussed for the previous scenario. There is one difference. In this case, it is assumed to be a second mission to Mars where new technologies are added to the Mars minimal closure scenario. This will use the same generic technologies as in the Mars fifty percent closure scenario. However, it will be given the accumulated CO_2, grey water, urine, and feces from the end of the Mars minimal closure scenario, hence representing the case that the crew is arriving to an existing base governed by the first scenario.

RESULTS AND DISCUSSION

MARS MINIMAL CLOSURE CASE STUDY

Figure 7 shows the amount of each material that is consumed. This is essentially how much would have to be shipped from Earth. By over an order of magnitude, water is the most consumed material with over 137,000 kg over a 750 day period. Note that the mass is displayed on a logarithmic axis because the water requirement is much larger than the others. As expected, given the significant water requirement, Figure 8 shows that grey water is the most generated material. Again, a logarithmic scale is used to clearly show the other materials that are generated. These results ignore any extra requirements for the small amount of crops that are also being grown. However, assuming that all of the water vapor generated from transpiration can be condensed, the small amount of crops does not significantly impact the results.

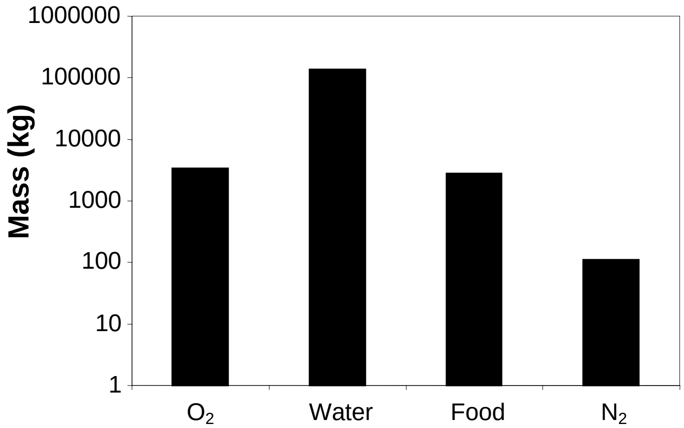

Figure 7: Mass of Material Shipped from Earth for Minimal Closure Scenario

Table 2 shows the required storage volumes of all of the materials that are either consumed or generated. In the case of the shipped material, the storage volume corresponds to the beginning of the mission when nothing has been consumed. In the case of the generated material, the storage volume corresponds to the end of the mission once everything has been generated. The assumption is that all of the waste that is generated will be stored within the base. For this scenario and all of the subsequent ones, the gases are assumed to have been compressed to fit within the required storage tank volume.

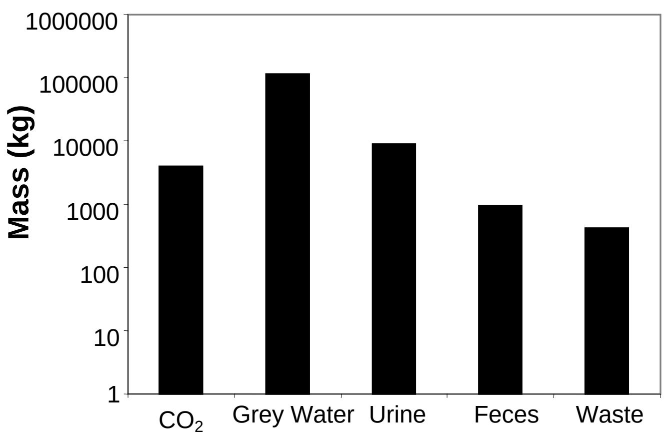

Figure 8: Mass of Materials Generated During the Course of the Minimal Closure Scenario

An initial vision of what such a Mars Base would look like is illustrated in Figure 9. We assumed that storage modules from Earth would have a volume equal to the shuttle's payload. Based on the shuttle payload volume of roughly 300 cubic meters, all of the water and food that is required would fit within one storage module, along with room for all of the grey water that would eventually be generated. Therefore, as shown by Figure 9, only one storage module and one living module would be required.

Table 2: Required Storage Volumes for Mars Minimal Closure Scenario

Material	Required Storage Volume (m^3)
O_2	12.9
Water	137
Food	2.19
N_2	0.47
CO_2	10.9
Grey Water	113.4
Urine	8.85
Feces	0.93
Waste	9.79

Inflatable modules, which could be sent in the one storage module, would be used for the small amount of crop growth and to store non-grey water waste. Each of these would require only one inflatable module. Finally, O_2, N_2, and CO_2 would be stored in three containers that could be sent in the empty volume of the storage module, and then unloaded later. The containers are at a pressure of 20,700 kPa. The only other significant requirement would be for 1 SP 100 reactor to power the entire base (the reactor is not visible in Figure 9 due to angle). This would have to be sent separately. The solar panels are used for experimental purposes and are only shown as a consideration. In this design, they do not contribute to providing energy for the facility.

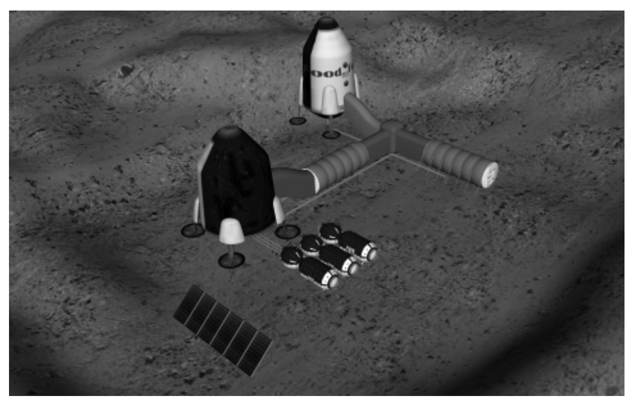

Figure 9: Scenario 1 – Minimal Closure

MARS FIFTY PERCENT CLOSURE CASE STUDY

Figure 10 shows the requirements for the Mars fifty percent closure scenario. Figure 11 shows the amount of material generated for the scenario. Significantly less food and water are required in the fifty percent closure scenario than in the previous scenario. In addition, due to the crops, O_2 is actually generated. This is because the plant area required to grow the necessary food (based on the assumed planting cycles) generates more O_2 than is required by the six crewmembers. However, at the same time, CO_2 is required because the six crewmembers do not generate enough CO_2 to support the requirements of the crops. Also, due to the water recovery, there is almost no accumulation of grey water.

Instead, there is an accumulation of untreatable waste that is due to the grey water that cannot be recovered. This is a direct result of the assumption that any untreatable grey water cannot be further recovered (e.g. combusted) so it must become untreatable waste.

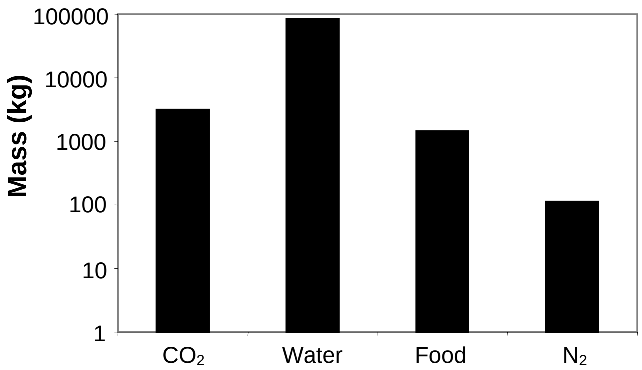

Figure 10: Mass of Materials to be Shipped from Earth for Mars Fifty Percent Closure Scenario

Table 3 shows the amount of volume that is taken up by material that is shipped to Mars and the material that is eventually generated. In the case of the shipped material, the storage volume corresponds to the beginning of the mission when nothing has been consumed. In the case of the generated material, the storage volume corresponds to the end of the mission once everything has been generated.

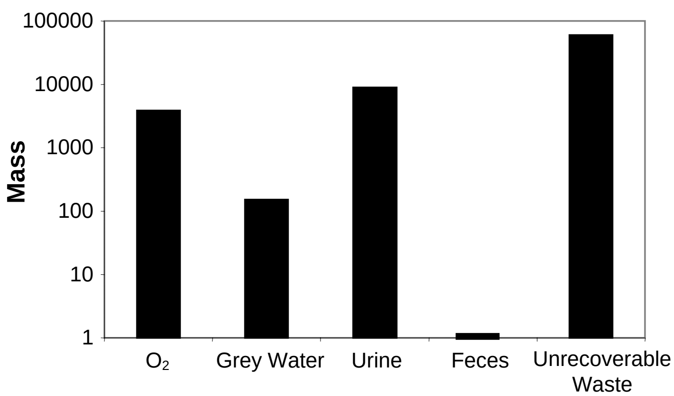

Figure 11: Mass of Materials Generated During the Mars Fifty Percent Closure Scenario

As shown in Figure 12, the facility is significantly larger than the minimal closure case study. This is primarily due to the crops. All of the additional inflatable modules are used for crop growth. Furthermore, the addition of the crops results in a significant increase in the amount of required energy. Therefore, unlike the previous case there are now 6 SP 100 reactors and several solar panels. There is no need for additional storage modules beyond the one that was in the previous case.

Table 3: Required Storage Volumes for Mars Fifty Percent Closure Scenario

Material	Required Storage Volume (m^3)
O_2	14.34
Water	82.8
Food	1.12
N_2	0.48
CO_2	8.58
Grey Water	0.15
Urine	8.85
Feces	0.13
Unrecoverable Waste	60.0

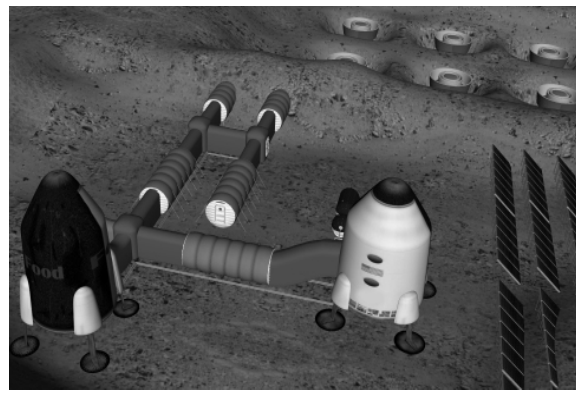

Figure 12: Scenario 2 – Fifty Percent Closure

MARS EVOLUTION CLOSURE CASE STUDY

Figure 13 shows the requirements for the Mars evolution closure scenario. Figure 14 shows the amount of re-generated material for the scenario from the first camping trip mission. As with the fifty percent closure scenario, significantly less food and water are required than in the minimal closure case. However, in comparison with the fifty percent closure scenario, far less water is required to be shipped from Earth. This is due to the fact that the stored grey water from the previous mission (i.e. the minimal closure scenario) is used as a recovery source to generate potable water. In the previous case study, CO_2 must be shipped from Earth (or obtained from the atmosphere) in order to grow the necessary amount of crops. In this scenario, the stored CO_2 from the previous mission can be used to supply the CO_2 that would have been sent from Earth in the previous scenario. Also, in the previous scenario, there was no significant storage requirement for grey water because it was all processed on the day after it was accumulated. In this scenario, it is necessary to store grey water because it will still be there from the first scenario. Finally, the urine storage requirement is greater because it is necessary to store both the amount generated from the previous mission and from this mission.

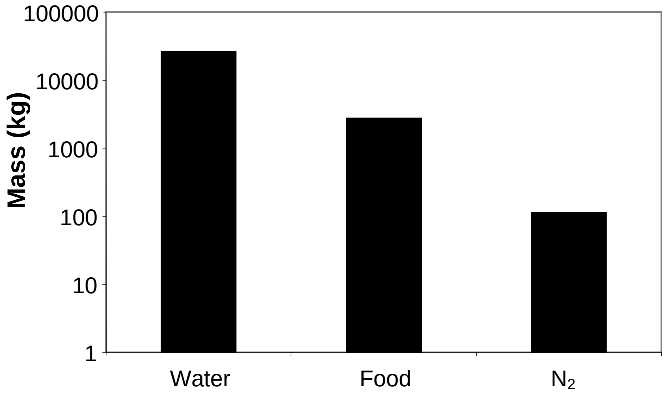

Figure 13: Mass of Materials to be Shipped From Earth for Mars Evolution Closure Scenario

One issue to consider is that these initial sources of water and CO_2 represent one-time sources. In this case water generated from the grey water is used up during the 750 day duration. There is no new source of grey water because it assumed to be immediately sent to be recovered. The CO_2 is not used up during the 750 day duration because only 3150 kg of CO_2 are required (as indicated in the fifty percent closure scenario), which is less than the surplus from the first mission. However, if there were future rotations, the source of CO_2 would eventually be depleted. Therefore, without additional modifications to the facility (such as recovery from untreatable waste), future rotations would eventually be similar to the fifty percent closure case study.

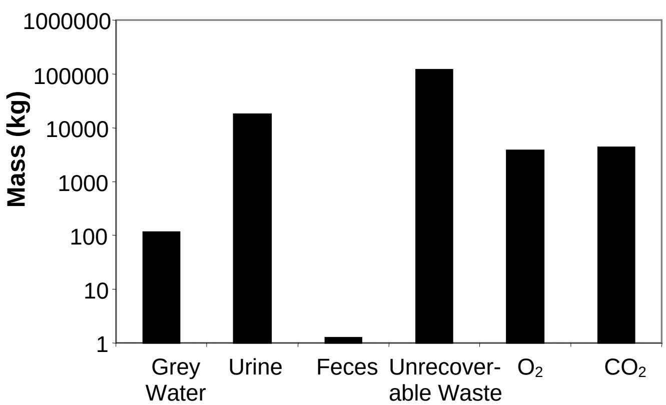

Figure 14: Required Storage Mass for Generated Materials for Mars Evolution Closure Scenario

Another issue to consider is that the facilities that are there during the first mission will be used to store additional material during the second mission. Therefore, they need to be designed such that they hold enough material in order to get through the entire evolution of the base. In this case, the best example of this is CO_2. At the end of the first mission, the CO_2 storage container only holds 4000 kg of CO_2. However, during the second mission, that total goes up to about 4300 kg until the plants begin to require more CO_2 than is generated. This occurs because there is some time in the second mission before the plants use more CO_2 than is generated by the crewmembers. Therefore, this temporary increase in the amount of stored CO_2 should be considered during the initial design of the habitat. In general, this would mean that an evolutionary design must not only look back for what resources it can use, but must also look forward so that the current design accounts for future situations.

Table 4: Required Storage Volumes for Mars Evolution Closure Scenario

Material	Required Storage Volume (m3)
O_2	14.3
Water	26.1
Food	2.18
N_2	0.48
CO_2	11.7
Grey Water	113.43
Urine	17.7
Feces	0.01
Unrecoverable Waste	117.8

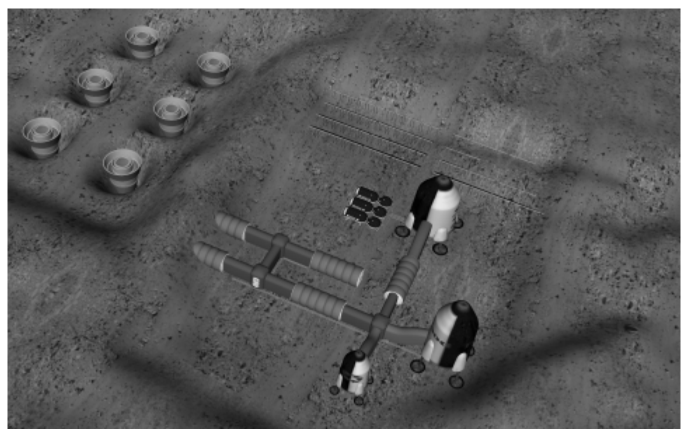

Figure 15: Scenario 3 - Evolution Closure

As illustrated in Figures 15 and 16, there is a significant increase in area of the overall facility relative to that of the minimal closure scenario. As before, several more inflatable modules are required to house the crop growth and the water recovery processes. Also, there are again 6 SP 100 reactors and several solar panels. The most significant difference between this scenario and the fifty percent closure scenario is that an extra storage module is required. This is because this scenario is assumed to occur after the minimal closure scenario. Therefore, any new material would have to be shipped to Mars from Earth. That is represented by the second storage module. Since this is an evolution from the minimal closure scenario, the additional nuclear reactors, the additional solar panels, and the additional inflatable modules would also have been shipped in between the two scenarios.

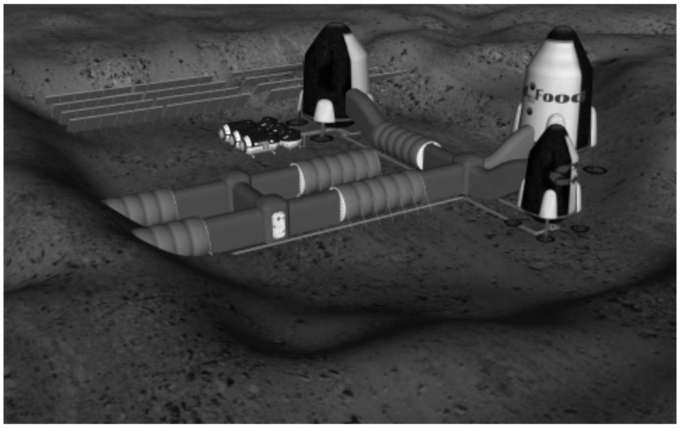

Figure 16: Scenario 3 - Evolution Closure (different angle)

CONCLUSIONS

In this paper, we presented a simulation tool that uses an XML language to easily swap in and out various systems. This plug and play capability will be useful for generating and conducting a large number of case studies. We integrated this numerical simulation model with a 3D virtual environment simulation system to interactively and dynamically visualize different scenarios in a realistic environment. We also presented results of three demonstration case studies. The first two compared the difference between a first mission to Mars with minimal closure versus a first mission to Mars with fifty percent closure. The final case study considered how the fifty percent closure mission would be affected if it occurred after the minimal closure mission. In this case, there was a significant reduction in the amount of required resources since it was possible to recover waste material that was generated in the previous mission. These results show that considering base evolution adds a new layer of complexity when conducting trade studies and evaluating design options.

The focus of this work was demonstrating the power and applicability of the SCOPE architecture to habitat prototyping by introducing the habitat evolution view rather than generating recommendations that would optimize how a MARS habitat should evolve. However, the architecture supports optimization by introducing planning and optimization nodes and agents, e.g. centralized management of a supply chain through a "Headquarters" node as presented in Orcun *et.al*. Furthermore, as this architecture is utilized to study different scenarios the model library will expand which in turn will make prototyping additional scenarios even quicker by reusing the models already in the library.

The scientific visualization (via virtual reality) component of the environment attempts to depict how the Mars surface habitat would look based on the simulation results. This visualization is able to vary dynamically due to simulation results by re-configuring predefined scalable objects (tanks, inflatable structures, etc) and indicators for their contents, e.g. gauges for gas tanks.

Therefore, the environment introduced in this work significantly helps us to tackle the new layer of complexity introduced as a result of considering habitat evolution. The natural extension of this work will be incorporating optimization agents and constructing trade studies that will help resolve ALS design challenges.

ACKNOWLEDGMENTS

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ADDITIONAL SOURCES

Mars Surface Habitat, NASA Images

Mars Surface Habitat, www.marshome.org

Mars 3D Rover Images (Spirit & Opportunity) NASA/JPL

DEFINITIONS, ACRONYMS, ABBREVIATIONS

A: The Fraction of PPF Absorbed by the Plant Canopy

ALS: Advanced Life Support

Amax: The Maximum Fraction of PPF Absorbed by the Plant Canopy

Area: Total Crop Area (m^2)

c: CO_2 Consumption Parameter which is a combination of four terms (See Volk *et al.*, 1995)

CO2_ppm: Parts per million of CO_2 in Cabin Atmosphere

h: Photo Period (hours)

n_i: Moles of Material i (e.g. H_2O, Carbohydrates, etc.)

$n_{i,e}$: Moles of Material i that becomes edible plant material (indicated by the e)

$n_{j,i}$: Moles of Material j that becomes inedible plant material (indicated by the i)

ppf: Photosynthetic Photon Flux

Q: Canopy Crop Quantum Yield

Qmax: Maximum Crop Canopy Quantum Yield

Qmin: Minimum Crop Canopy Quantum Yield

SCOPE: Supply Chain Optimization and Protocol Environment

ta: Time When Amax is Obtained (days)

tm: Time Until Harvest (days)

tq: Time Until Onset of Canopy Senescence

VBA: Visual Basic for Applications

x_i: Mole Fraction of i in Edible Portion of a Plant (i could be Carbohydrates, Fats, Proteins, or Water)

$x_{i,e}$: Mole Fraction of i in Edible Portion of a Plant (i could be Carbohydrates, Fats, Proteins, or Water)

$x_{j,i}$: Mole Fraction of j in Inedible Portion of a Plant (j could be Proteins, Fibers, or Lignins)

XML: Extensible Markup Language (See http://www.xml.org/)

APPENDIX A

CREWMEMBER EQUATIONS

These equations for the crewmember model are from the BIO-Plex Baseline Model Document (Finn, 1999).

Stoichiometric Reaction:

$$n_{Protein} + n_{Carbohydrates} + n_{fat} + n_{O_2} \rightarrow n_{CO_2} + n_{H_2O} + n_{Urine Solids} + n_{Feces Solids} + n_{Sweat Solids} \quad (1)$$

Carbon Balance:

$$4\, n_{Protein} + 6\, n_{Carbohydrates} + 16\, n_{fat} = n_{CO_2} + 2\, n_{Urine Solids} + 42\, n_{Feces Solids} + 13\, n_{Sweat Solids} \quad (2)$$

Hydrogen Balance:

$$5\, n_{Protein} + 12\, n_{Carbohydrates} + 32\, n_{fat} = 2\, n_{H_2O} + 6\, n_{Urine Solids} + 69\, n_{Feces Solids} + 28\, n_{Sweat Solids} \quad (3)$$

Oxygen Balance:

$$n_{Protein} + 6\, n_{Carbohydrates} + 32\, n_{fat} + 2\, n_{O_2} = 2\, n_{CO_2} + n_{H_2O} + 2n_{Urine Solids} + 13\, n_{Feces Solids} + 13\, n_{Sweat Solids} \quad (4)$$

Nitrogen Balance:

$$n_{Protein} = n_{Urine Solids} + n_{Feces Solids} + n_{Sweat Solids} \quad (5)$$

The equations for the amount of protein, carbohydrates, and fats are derived from the assumed diet in the BIO-Plex Baseline Document and from the mass fractions of protein, carbohydrates, fats, and water in the respective plants.

Protein Amount:

$$n_{Protein} = n_{Wheat} * x_{Protein\ Wheat} + n_{Rice} * x_{Protein\ Rice} + n_{Peanut} * x_{Protein\ Peanut} + n_{Potato} * x_{Protein\ Potato} + n_{Soy} * x_{Protein\ Soy} \pm 0.1(\text{random}) \quad (6)$$

Carbohydrate Amount:

$$n_{Carbohydrate} = n_{Wheat} * x_{Carbohydrate\ Wheat} + n_{Rice} * x_{Carbohydrate\ Rice} + n_{Peanut} * x_{Carbohydrate\ Peanut} + n_{Potato} * x_{Carbohydrate\ Potato} + n_{Soy} * x_{Carbohydrate\ Soy} \pm 0.1(\text{random}) \quad (7)$$

Fat Amount:

$$n_{Fat} = n_{Wheat} * x_{Fat\ Wheat} + n_{Rice} * x_{Fat\ Rice} + n_{Peanutt} * x_{Fat\ Peanut} + n_{Potato} * x_{Fat\ Potato} + n_{Soy} * x_{Fat\ Soy} \pm 0.1(\text{random}) \quad (8)$$

Urine Solids Ratio:

$$\frac{n_{Urine Solids}}{\left(n_{Urine Solids} + n_{Feces Solids} + n_{Sweat Solids}\right)} = 0.797 \quad (9)$$

Feces Solids Ratio:

$$\frac{n_{Feces Solids}}{\left(n_{Urine Solids} + n_{Feces Solids} + n_{Sweat Solids}\right)} = 0.174 \quad (10)$$

CROP EQUATIONS

These equations for the crop model are from the BIO-Plex Baseline Model Document. These are generic equations for any crop. The parameters and constants will be different depending on the crop.

Edible Material Growth Stoichiometric Reaction:

$$n_{CO_2,e} + n_{H_2O,e} + n_{HNO_3,e} \rightarrow n_{Protein,e} + n_{Carbohydrates} + n_{Fat} + n_{O_2,e} \quad (11)$$

Inedible Material Growth Stoichiometric Reaction:

$$n_{CO_2,i} + n_{H_2O,i} + n_{HNO_3,i} \rightarrow n_{Protein,i} + n_{Fiber} + n_{Lignin} + n_{O_2,i} \quad (12)$$

Edible Material Carbon Balance:

$$n_{CO_2,e} = 4\, n_{Protein,e} + 6\, n_{Carbohydrates} + 16\, n_{Fat} \quad (13)$$

Edible Material Hydrogen Balance:

$$2\, n_{H_2O,e} + n_{HNO_3,e} = 5\, n_{Protein,e} + 12\, n_{Carbohydrates} + 32\, n_{Fat} \quad (14)$$

Edible Material Oxygen Balance:

$$2\, n_{CO_2,e} + n_{H_2O,e} + 3\, n_{HNO_3,e} = n_{Protein,e} + 6\, n_{Carbohydrates} + 2\, n_{Fat} + 2\, n_{O_2,e} \quad (15)$$

Edible Material Nitrogen Balance:

$$n_{HNO_3,e} = n_{Protein,e} \quad (16)$$

Inedible Material Carbon Balance:

$$n_{CO_2,i} = 4\, n_{Protein,i} + 6\, n_{Fiber} + 10\, n_{Lignin} \quad (17)$$

Inedible Material Hydrogen Balance:

$$2\, n_{H_2O,i} + n_{HNO_3,i} = 5\, n_{Protein,i} + 10\, n_{Fiber} + 11\, n_{Lignin} \quad (18)$$

Inedible Material Oxygen Balance:

$$2\, n_{CO_2,i} + n_{H_2O,i} + 3\, n_{HNO_3,i} = n_{Protein,i} + 5\, n_{Fiber} + 2\, n_{Lignin} + 2\, n_{O_2,i} \quad (19)$$

Inedible Material Nitrogen Balance:

$$n_{HNO_3,i} = n_{Protein,i} \quad (20)$$

Edible Protein Ratio:

$$\frac{n_{Protein,e}}{\left(n_{Protein,e} + n_{Carbohydrates} + n_{Fat}\right)} = x_{Protein,e} \qquad (21)$$

Edible Carbohydrates Ratio:

$$\frac{n_{Carbohydrates}}{\left(n_{Protein,e} + n_{Carbohydrates} + n_{Fat}\right)} = x_{Carbohydrates,e} \qquad (22)$$

Inedible Protein Ratio:

$$\frac{n_{Protein,i}}{\left(n_{Protein,i} + n_{Fiber} + n_{Lignin}\right)} = x_{Protein,i} \qquad (23)$$

Inedible Fiber Ratio:

$$\frac{n_{Fiber}}{\left(n_{Protein,i} + n_{Fiber} + n_{Lignin}\right)} = x_{Fiber,i} \qquad (24)$$

CO_2 Consumption:

$$n_{CO_2,e} + n_{CO_2,i} = 0.0036 * \text{area} * \left[\left(c * h\right) - \left(\left(24 - h\right) * \left(1 - c\right)\right)\right] * \text{ppf} * Q * A \qquad (25)$$

Dry Biomass Growth:

$$\frac{\left(83\, n_{Protein,e} + 180\, n_{Carbohydrates} + 256\, n_{Fat}\right)}{\left(83\, n_{Protein,e} + 180\, n_{Carbohydrates} + 256\, n_{Fat} + 83\, n_{Protein,i} + 162\, n_{Fiber} + 163\, n_{Lignin}\right)} = 0.4 \qquad (26)$$

Fresh Water Requirement for Edible Biomass:

$$\frac{18\, n_{Edible\ H_2O}}{\left(18\, n_{Edible\ H_2O} + 83\, n_{Protein,e} + 180\, n_{Carbohydrates} + 256\, n_{Fat}\right)} = 0.06 \qquad (27)$$

Fresh Water Requirement for Inedible Biomass:

$$\frac{18\, n_{Inedible\ H_2O}}{\left(18\, n_{Inedible\ H_2O} + 83\, n_{Protein,i} + 162\, n_{Fiber} + 163\, n_{Lignin}\right)} = 0.5 \qquad (28)$$

Crop Area Equation:

$$A = \frac{\left(A_{max} * \text{age}\right)}{\left(t_a^5 + \text{age}^5\right)^{1/5}} \qquad (29)$$

Crop Q Equation:

$$Q = \frac{\left(Q_{max} - Q_{min}\right) * \left(t_m - \text{age}\right)}{\left(\left(t_m - t_q\right)^{15} + \left(t_m - \text{age}\right)^{15}\right)^{1/15}} \qquad (30)$$

Crop Qmax Equation:

$$Q_{max} = \frac{0.066 * \text{co2\_ppm}}{\left(210^{1.4} + \text{co2\_ppm}^{1.4}\right)^{1/1.4}} \qquad (31)$$

Water Transpiration Rate:

$$n_{H_2O,Trans} = 55.56\ \text{area}\left(\frac{\left(1.1338 + 0.0070423\ \text{ppf}\right)\text{age}}{\left(t_{cc}^7 + \text{age}^7\right)^{1/7}}\right) \qquad (32)$$

APPENDIX B

MODEL ASSUMPTIONS

Table 5: General Assumptions for All Scenarios

Crewmembers	6. Nominal value from Table 3.1.1 of the BVAD (Hanford, 2004A)
Duration	The mission duration is set to be 750 days. This is to avoid startup effects in the actual simulation of the model. In terms of the actual results, it is arbitrary.
Cooling Power Requirement	Cooling requirement is set equal to energy requirement for the habitat.
Energy Resources	Energy can only be provided by SP 100 Nuclear Reactors and by Solar Panels (latter two scenarios).

Table 6: Food Assumptions for All Scenarios

Assumption	Explanation
Consumed and Grown Food	Food is listed as Carbohydrates, Fats, and Proteins
Daily Crewmember Protein Requirement	Sum of Protein from daily crewmember requirements of wheat, rice, peanuts, potatoes, and soy from BIO-Plex Baseline Document (Finn, 1999) + or – a random offset of at most 5% of the above total.
Daily Crewmember Fat Requirement	Sum of Fat from daily crewmember requirements of wheat, rice, peanuts, potatoes, and soy from BIO-Plex Baseline Document (Finn, 1999) + or – a random offset of at most 5% of the above total.
Daily Crewmember Carbohydrate Requirement	Sum of Carbohydrates from daily crewmember requirements of wheat, rice, peanuts, potatoes, and soy from BIO-Plex Baseline Document (Finn, 1999) + or – a random offset of at most 5% of the above total.
Food Storage Power Requirements	The power requirements are directly from Table 6.13 of the FY05 ALS Metric (Hanford, 2005)

Table 7: Atmosphere Assumptions for All Scenarios

Assumption	Explanation
Upper and Lower Constituent Bounds	Specified in Table 4.1.1 of the BVAD (Hanford, 2004A)
Model maintains the daily amount of each constituent within the bounds.	
Anything in excess is assumed to be completely removed and sent to storage for that constituent.	
Leakage	One percent of the daily total (by mass) of each constituent is assumed to be leaked to the atmosphere.
Water Vapor	All excess water vapor can be recovered as potable water.
Energy Requirements	CO_2 Removal, Pressure Control, Gaseous Trace Contaminants, Atmosphere Composition Monitoring, and Fire Detection System are all assumed to exist. The requirements are directly from Table 6.13 of the FY05 ALS Metric (Hanford, 2005)

Table 8: Assumptions for Closure and Closure Evolution Scenarios

Assumption	Explanation
Grey Water Recovery Fraction	The recovery fraction for grey water is set at 0.5. This has been arbitrarily set to be consistent with the 50% closure scenario. The rest becomes untreatable waste.
Water Treatment Power Requirements	Water Treatment, Process Controller, Water Quality Monitoring, and Product Water Delivery System are all assumed to have power requirements directly from Table 6.13 of the FY05 ALS Metric (Hanford, 2005)
Waste Combustion Carbon Content	The Carbon Content of the Combustible Waste has been set at 0.5.
Waste Combustion Recovery Fraction	The Recovery Fraction of the Combustible Waste has been set at 0.5 to be consistent with the 50% closure scenario. The rest becomes untreatable waste.
Untreatable Waste	This waste must be stored and cannot be converted into anything useful.
Evolution Closure Scenario Starting Conditions	All of the stored material at the end of the minimal closure scenario is there at the beginning of the evolution closure scenario.

Table 9: Crop Assumptions for All Scenarios

Assumption	Explanation
Generic Crop	A generic crop assumes that the protein, fat, and carbohydrate content are weighted to provide all of the daily requirements in one crop as opposed to several. Parameters for the crop are listed above in Table 1.
Crop Schedule	For each growing cycle, all of the required crops will be planted at one time and then harvested at one time (since a generic crop is being used). There are multiple growing cycles during the duration of the mission.
Crop Intermission Period	There is a 30 day crop intermission period after each harvest. This is assumed to be time spent to prepare the area for new crops.
Energy	The ballasts and lamps detailed in Table 4.2.2 of the BVAD are used.

Table 10: Facility and Storage Assumptions

Assumption	Explanation
Storage Module Volume	300.24 m^3. This is based off of the shuttle payload volume.
Storage Tank Pressure	20,700 kPa
Storage Tank Maximum Volume	14.3 m^3 based off of requirements specified by model results.
Inflatable Volume	44.5 m^3. This is an arbitrary assumption.
Waste Storage Power Requirements	Waste Water Storage and Solid Waste Collection are directly from Table 6.13 of the FY05 ALS Metric (Hanford, 2005)
Water Storage Power Requirements	Directly from Table 6.13 of the FY05 ALS Metric (Hanford, 2005)