Space Hotel Design: Preliminary Structural Design and Cost Estimation

Software Designed to Determine Preliminary Cost Estimate Based on Human Factors and Structural Design

16.851 Satellite Engineering

Massachusetts Institute of Technology, Cambridge, MA
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Motivation

Throughout history, people have been fascinated with exploring outer space. Until recently, only astronauts have had the privilege of being able to experience life in outer space. However, in 2001, the first space tourist, Dennis Tito, traveled to the International Space Station onboard a Russian Soyuz rocket.

The travels of Dennis Tito are just the beginning for space tourism. A new space tourism industry would be an entirely new commercial use of space and a huge potential new market. Space tourism may encourage other private investment in the use of space, which may in turn support significant future space exploration.

Problem Statement

Design a concept for a Space Hotel orbiting Earth. Create a CAD model of the hotel to “rough-out” the structural design as well as visualize the concept. The Space Hotel should provide all the amenities required by a tourist. These amenities should include gravity, power, food, water, and waste removal.

Design a MATLAB module to size the hotel structure as well as estimate the requirements for supporting human life. The user will set the number of hotel guests and the duration of the stay of each guest on the Space Hotel. These inputs will be the driving factors for the concept design. Based on the design concept for the hotel, estimate the costs involved in launching, assembling, and operating the hotel. The module will investigate cost with respect to the number of guests and the duration the stay of each guest.

Introduction

First, a conceptual design is created of the Space Hotel. A CAD model of the hotel is created with enough detail to present the rough conceptual design of the Space Hotel.

The spin rate of the hotel in order to produce artificial gravity is determined. Also, determine the other needs of the human guests of the hotel are determined. These needs will include electricity, food, water, waste removal, and crew.

Cost models are developed to estimate the cost for launch, assembly, and operation of the hotel. Using these cost models, the cost with respect to the number of guests and the duration of the stay of each guest is determined. In addition, trends are shown which illustrate how a Space Hotel can be operated in a cost-efficient manner.

Space Hotel Structural Design

Components

The Space Hotel consists of four main components: habitation modules, nodes, a center module, and connecting modules between the habitation modules and the center module. Figure 1 shows the configuration of the Space Hotel.

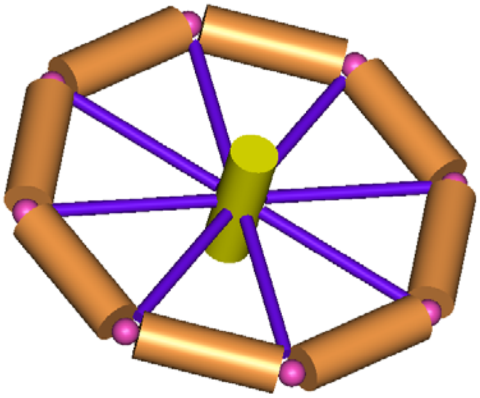

Figure 1 Isometric view of Space Hotel

All four components are visible in Figure 1, above. The large cylindrical components in the shape of a ring are the habitation modules. The spherical-shaped objects in between the habitation modules are the nodes. The long, thin, cylindrical components connecting the nodes to the center component can be seen as well. The large cylindrical component in the middle is the "center module."

Habitation Modules

The habitation modules are broken up into several compartments for hotel guests to live in. In addition, there is a large volume inside the module reserved for equipment to maintain the station as well as other storage space.

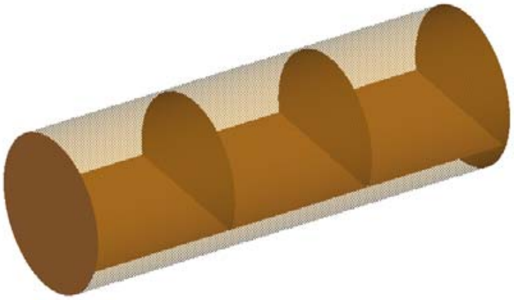

Figure 2 Habitation module internal compartments

The habitation modules are design in order to fit inside a realistic launch vehicle fairing. For the purposes of this project, an Atlas V, 5-meter fairing was chosen. The Atlas V is a likely launch vehicle to be used to launch components for a Space Hotel into orbit. The figure below shows one of the habitation modules fitting inside the launch vehicle fairing envelope.

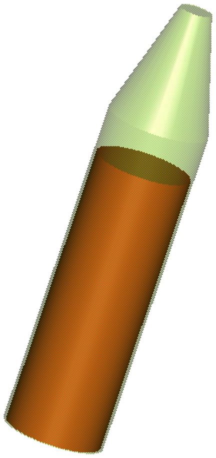

Figure 3 Habitation module inside Atlas V fairing

In addition, the size and shape of the habitation module is limited by the payload mass capability of the Atlas V launch vehicle. The estimated mass of one of the habitation modules, which is explained later in this paper, is roughly 10,000 kg. This mass is less than the payload capability of the Atlas V launch vehicle to many LEO orbits. For example, the Atlas V has the capability of launching 20,050 kg into a 185 km altitude, 28.5 degree inclination orbit.[i]

Nodes

The spherical shaped components between the habitation modules are simply interconnecting nodes which allow guests to transfer from one habitation module to another as well as to the center module. The spheres in the picture are simply placeholders for the components in a more detailed design.

Connecting Cylindrical Components

The long, thin, cylindrical components connecting the nodes to the center component are simply tubes which allow hotel guests to pass from the habitation module section of the hotel to the center module.

Center Module

The center module of the hotel is designed to roughly the same dimensions as the habitation modules in order for it to fit inside the same launch vehicle fairing. The purpose of the center module is to allow the hotel guests the experience of floating in a zero-gravity environment. Leisure activities can be held in this section of the hotel.

Life Support System

Our Space Hotel is situated in orbit around the earth, where the environment system for the passengers of the hotel is isolated except for the periodical supply by space transportation systems.

To support the life of passengers in the space environment, specific needs need to be met. The basic needs are the appropriate air composition, temperature, and humidity which should be maintained continuously. The consumables such as food and water should be supplied on passengers' demands. Wastes should be separately stored or removed periodically to maintain the optimal mass of the hotel and to keep the cleanliness.

In addition to those metabolic needs and effluents of humans, other supplies such as food preparation device, face/hand washing water, urinal flushing and etc should be also included. For a facility which stays in the space environment for a long period, such as our Space Hotel, or International Space Station, functions such as O2 recovery and recycling of waste water and solid waste become important to keep the re-supply and storage expenses from becoming too high.

ECLSS

The current state-of-the-art system for long duration life support is embodied in the International Space Station (ISS) environmental control and life support system (ECLSS). ECLSS includes the function of providing a habitable environment, including clean air and water, plus solid waste processing, food processing, biomass production and thermal control, and supporting interfaces with other subsystems.

Considering the similar nature of the ISS and our Space Hotel, such as a durable structure for a long stay in the space environment, the choice was made to use ECLSS for our Space Hotel. In the following section, the details of each requirement and corresponding ECLSS device which satisfy the need will be presented.

Supporting System to meet Human Requirements

Interior Space

The ISS model is again utilized to estimate the personal volume necessary to experience a comfortable stay at our Space Hotel. In the limited space inside the structure, the astronauts rest, sleep (in a separate section), eat, shower, and also exercise on treadmills on the ISS. The volume of personal space on the ISS was calculated by dividing the volume of the habitat module by the number of the crewmembers, and was computed to be 645.6 (ft^3/person). This number was feasible considering that the minimum volume requirement calculated by Breeze (1961)[ii] was:

50ft^3/person	(1-2 days)
260 ft^3/person	(more than 1 or 2 months)
600 ft^3/person	(for more than 2 months)

The mission length of the space station is between 3-6 months.

However, there are three concerns that we have to think about:

- The nature difference between ISS and Space Hotel. More space required for comfort
- Weightless state which allows passengers to utilize the space well is unavailable inside our Space Hotel. With the artificial gravity, more space is needed.
- Less space per person is needed as crew size increases

2. Thermal system

Although people can endure a relatively wide range of temperature and humidity conditions, the proper range in the habitat is important to maintain high work efficiency. For our hotel, it is crucial to provide comfort as a service. The ideal temperatures range from 18 to 27 C (65 to 80 F) and "ideal" humidity ranges from dew points of 4 to 16 C (40 to 60 F). Thermal management is divided into two systems, the internal and external thermal control systems. The former includes the avionic air assemblies which provide air-cooling for equipment, the common cabin air assemblies which control cabin air, condensate storage, and the water flow loops for hear transport. The external control system is included in the assessed cooling-mass penalty.

Food subsystem

Food will be provided in individual entrees from Earth. A mix of fresh, dehydrated, and full-water preserved, shelf-stable or frozen food will be used. This system required the significant amount of packaging. Supporting technology includes freezers and some food preparation equipment.

Air

In order to generate air conditions as close as the atmospheric configuration, oxygen, carbon dioxide, nitrogen, water vapor, trace contaminants, dust, and smoke particles are used as the components in the space habitats. Four separate systems, CO2 removal, CO2 reduction, O2 generation, and trace gas contaminants control systems, works to revitalize the air and maintain the quality of the air. Regenerative CO2 removal equipment based on molecular sieve technology, which does not require periodical replacement or storage space, is installed in the ISS ECLSS. CO2 Reduction is necessary to extract O required to generate O2. For a structure designed for the longer stay in the apace, the loss of the mass of CO2 leads to increased storage or re-supply requirements. O2 generation maintains sufficiently high oxygen partial pressure (21.4 kPa at near sea-level). Trace gas contaminants control systems is important in a closed structure like the Space Hotel because the volume is limited relative to containment sources. In addition, Atmosphere Control and Supply system is required to maintain proper composition and pressure of the air during the flight. The following chart shows the flow of air component in a recycle loop. This flowchart was extracted from a design report written by NASA.[iii]

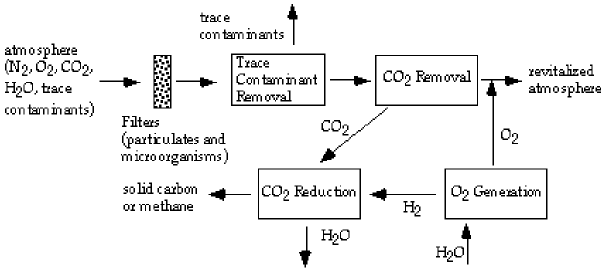

Figure 4 Atmosphere control and supply

Water

Ensuring a clean supply of potable water and water for bathing is essential. Water management consists of three parts, water storage and distribution, water recovery, and water quality monitoring.

For water recovery, urine is processed by vapor compression distillation, which claims 88 percent water recovery. The brine is either returned to Earth or dumped. The water processor deals with all unconfirmed water such as hygiene water, effluent from the vapor compression distillation, and condensation from dehumidification.

When recycled waste water is used, the potential for contamination is higher than when using stored water. Thus, process control water quality monitor provides water quality assurance. The following chart shows the flow of water management systems, extracted again from the report by NASA.[iv]

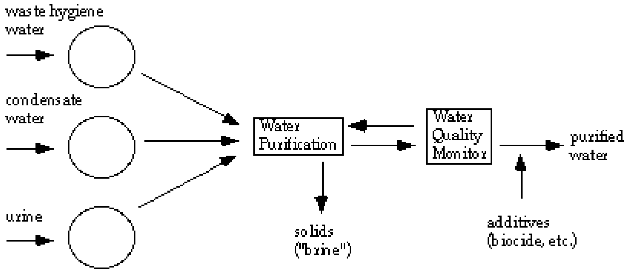

Figure 5 Water recovery and management

6. Waste Subsystems

The wastes generated on a space habitat can be classified into four general types: metabolic wastes consisting of moist solids including feces and vomit, other solid wastes, liquid wastes including urine and waste hygiene water, and gaseous wastes. For long duration missions this mass lost when the waste is dumped becomes prohibitive and methods are needed to recover to useable products as much mass as possible. On ISS, urine is recycled as explained in the Water section. Solid waste is stored and returned on the transfer vehicle or burned upon re-entry in an expendable re-supply vehicle. The toilet is also included under the subsystems.

Other Considerations

Although omitted in our design of the Space Hotel, we could aim to provide an even higher grade comfortable environment. For example, additional devices to decrease the level of odor and noise, or some decorative interior lighting could be installed. Other possibilities are to expand recreational facilities such as a plant growth facility, and improve safety devices such as fire detection and suppression systems.

Mass Estimation

Mass estimation for each component of human requirement was calculated using the actual data from the ISS. The optimization of ECLSS design in terms of the lowest launch cost was computed applying of Equivalent System Mass as related to the mass volume, power cooling and crew time needs.[v] Considering that masses of most of the components are proportional to the number of crews and the duration, the values shown in the following table is calculated by simple division with the number of crews and the duration time of ISS. These values are part of inputs for software module described in the following section.

Table 1 Mass estimation of human requirements

Consumables		[kg/CM-d]	
Supply	Air	0.84	
		(+ 0.29)	tank mass
	Food	1.37	
		(+ 0.24)	deposable packaging
	Thermal	0.003515	
	Water	7	drink, food preparation, hand/face washing, and urinal flushing
	Clothing	1.6	including EVA clothe
Waste	Waste	0.15	
Infrastructure		[kg/CM]	
ISS ECLSS technology		20366	including air tank, food freezers, CO2 removal device, EVA support

Software Module

Structural Sizing Module

Requirements

The MATLAB module *structure.m* determines the mass of the Space Hotel and the required spin rate of the hotel to maintain 1g of artificial gravity in the habitation modules of the spacecraft.

Description of Code

The code uses the inputs of the number of guests and the duration of the stay of each guest to calculate the numbers and sizes of the various components in the Space Hotel. The code calculates the masses of each component in the hotel and outputs the total structural mass of the hotel.

Constants

The first constant used in this module is the gravitational acceleration constant, g. It is input into the module as being equal to 9.81 m/s^2.

The remaining constants are the "free volumes" of the habitation and center modules in the Space Hotel. These volumes are determined from the fairing size of the Atlas V 5-meter fairing as well as the payload lift capability of the launch vehicle. Taking these constraints into consideration, the habitation modules were determined to have a "free volume," V_{hab}, of approximately 4500 ft^3.

The center module was determined to have a "free volume" of approximately 4500 ft^3.

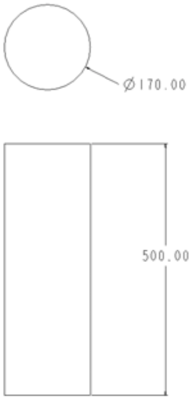

Figure 6 Dimensions of habitation and center modules (inches)

Inputs

N_guests: This input is the total number of people living onboard the Space Hotel at any given time.

duration (days): This input is the time each person living on the Space Hotel will spend onboard before they head back to earth.

Outputs

str_mass (kg): This output is the total structural mass of the entire Space Hotel. This is a sum of all of the habitation modules, the interconnecting cylindrical modules, as well as the center structural module.

spin_rate (m/s): This output is the spin rate of the Space Hotel which is required to create artificial gravity of 1g in the habitation modules of the hotel.

Theory & Equations

The first step in determining the structural mass of the hotel is to determine how much volume each guest of the hotel will need during his/her stay. In 1961, Breeze noted that a person on a space station should need approximately 50, 260, and 600 cubic feet of volume for durations on the space station of 2, 30, and 60 days, respectively. This is discussed in the "Supporting System to Meet Human Requirements" section earlier in this paper.

Since this is a Space Hotel and should be somewhat luxurious and relaxing for the hotel guests, the numbers provided from Breeze are multiplied by a factor of 3 to result in volumes of 150, 780, and 1800 cubic feet for durations of 2, 30, and 60 days, respectively. In addition, since it has been estimated that the minimum volume for a space station is 700 cubic feet per person[vi] and it is unlikely that any person would stay on the hotel for a short time (i.e. less than one week), the volume per person estimated here is reasonable.

In order to determine guest required volumes for durations between the data points given, linear interpolation was done. This can be seen below in Figure 7.

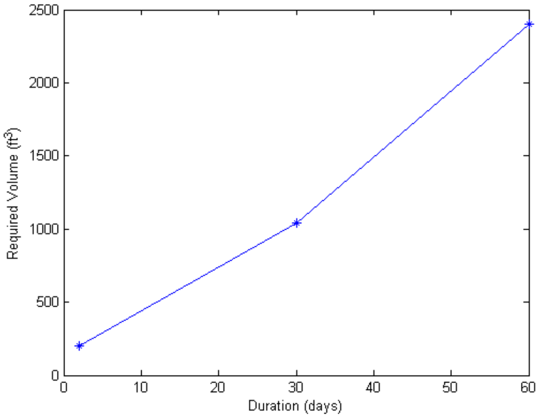

Figure 7 Linear interpolation of volume vs. duration

Next, the total required volume for the guests is calculated by multiplying the number of guests by the volume required per guest.

$$V_{total} = N\_guests * V_{guest} \qquad (1)$$

The number of habitation modules is then determined from the following equation and then rounding up to the next highest integer.

$$N_{hab} = \frac{V_{total}}{V_{hab}} \qquad (2)$$

Based on the sizing requirements given from the launch vehicle fairing constraints, the overall size of the habitation modules is then given. Next, the mass of the habitation modules is calculated. This is shown in the equation below.

$$m_{hab} = \rho_{hab} L\pi\left(r_{hab}^2 - (r_{hab} - t)^2\right) \qquad (3)$$

In the above equation, the density of the habitation module is given to be 0.103 lb/in^3 for a material of Aluminum 2219. The wall thickness, *t*, of the module is given to be 0.4 inches.[vii]

The calculated mass of each habitation module is augmented with additional mass for welds, weld lands, and thickness tolerances. This adds an additional 1% to the mass of the habitation module.[viii]

Next, an additional 10% is added to the mass to take into account the internal, non-load-bearing structure of the habitation module. This is an extremely rough estimate.

In addition, the mass of the required shielding to protect the hotel from space debris is added to the weight calculation. A Whipple Shield[ix] is used for this purpose. This requires an additional thin Aluminum covering around the outside of the habitation module. This additional Aluminum piece is 0.080 inches thick. The design of the Whipple Shield can be seen in the figure below.

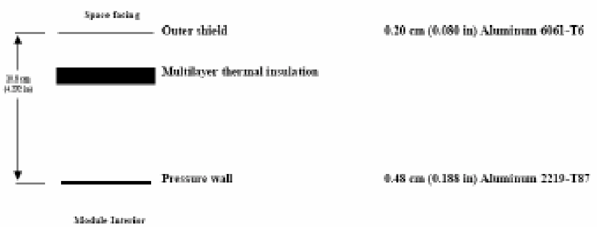

Figure 8 Example Whipple shield

Finally a factor of 1.5 is multiplied by the mass estimate due to the lack of design maturity and heritage.

The same procedure of calculating mass is done for the thin, cylindrical interconnecting structural members connecting the habitation modules to the center module. It is also done for the center module as well.

Finally, the spin rate of the hotel required to produce artificial gravity in the habitation modules is determined. The equation for centripetal acceleration is used. This is shown below.

$$a = \frac{V^2}{R} \qquad (4)$$

In order to keep a simulated gravity of 1g in the habitation modules, the value of *a* is set to g, which is 9.81 m/s^2, and the value of R is the radius of the Space Hotel to the ends of each habitation module. See the figure below to illustrate this.

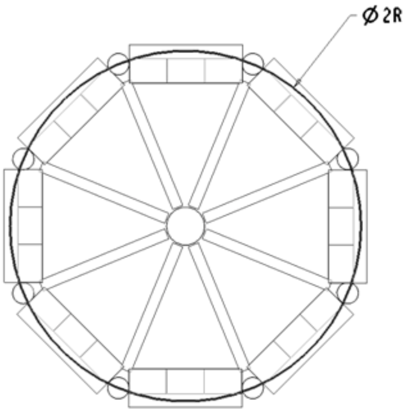

Figure 9 Radius of habitation module ring

In order to approximate the value of R for all sizes of the Space Hotel, the circumference of the ring of habitation modules is assumed to be equal to the lengths of the habitation modules plus the lengths of the nodes connecting the modules together. If this assumption is made, the radius can be determined form the equations 5a and 5b.

$$C = \pi D = N_{hab}(L + D_{node}) \qquad (5a)$$

$$R = \frac{D}{2} = \frac{C}{2\pi} = \frac{N_{hab}(L + D_{node})}{2\pi} \qquad (5b)$$

Rearranging equation 4 from above, the following equation produces the required spin rate, *V*, for the Space Hotel.

$$V = \sqrt{aR} \qquad (6)$$

Cost Model Module

Requirements

The MATLAB module *cost_model.m* estimates the cost of the Space Hotel including the construction costs, logistics, and operation costs.

Description of Code

The code uses the inputs of the number of guests, the duration of the stay of each guest, the number of years in operation, and the weight of the Space Hotel to calculate total cost. The code calculates the individual costs such as the space structure, the ground support costs and logistics. These are summed together for total cost.

Inputs

Years(yrs): This input is number of years the Space Hotel expects to be in operation.

n_crew: This input is number of people staying onboard the Space Hotel at any time

duration (days): This input is the time each person living on the Space Hotel will spend onboard before they head back to earth.

w_f (kg): This input is the weight of Space Hotel structure.

Outputs

total_cos ($): This output is the total cost of constructing and operating a Space Hotel for a particular number of years, a maximum capacity of crew, and for a specified duration.

Theory & Equations

Various cost factors that result from space facility designs and an estimation of rough order of magnitude cost are included in this cost model. The required investment areas addressed include the space segment, launch vehicles, operations, and logistics.[x]

Space Segment Cost:

The space segment cost is calculated using:

$$S_c = S_{cf} * P_{cf} * R_{cf} * W_f \qquad (7)$$

S_c: space segment cost ($)
S_{cf}: the price per kg of facility on orbit, for manned space programs the mean is 104 $K/kg
P_{cf}: the program cost normalized over the number of manned vehicles produced (non-dimensional)
R_{cf}: research, test, development, and engineering cost factor is used to compensate for new development cost. The R_{cf} should be 3 for new development programs, and 1 for a program based on existing hardware. We will use 2. (non_dimensional)
W_f: weight of facility (kg)

Launch Vehicle Cost:

The launch vehicle cost is calculated using:

$$L_c = L_{cf} * I_{cf} * W_f \qquad (8)$$

L_c: launch vehicle cost ($)
L_{cf}: launch cost factor estimated using historical data and planned cost goals for future development, a mean of 15.2 $K/kg ($/kg)
I_{cf}: insurance cost factor, 1/3 of the launch vehicle cost, will use then 1.333. (non-dimensional)

Ground Operation and Support:

A good estimate for the purposes of this model is $80M per year for yearly operations and support costs.

Logistics:

The logistic cost was calculated using:

$$W_{cl} = 365 * ((\delta_{cs} + \delta_{crew} + \delta_{cg}) * (N_c/E_c) + \varepsilon) \qquad (9)$$

W_{cl}: yearly crew logistics weight (kg)
δ_{cs}: equipment weight needed for crew support during the trip to and from orbit, assumed to be 2000 kg/person (kg/person)
δ_{crew}: weight/person (kg/person)
δ_{cg}: weight of gear/person (kg/person)

ε: consumption rate for the entire facility (kg/person-day)

$$W_{mm} = W_f * M_{mf} \qquad (10)$$

W_{mm}: materials yearly delivery weight W_{mm} (kg)
M_{mf}: maintenance materials weight fraction, assumed to be 0.01 for this model (non-dimensional)

$$W_l = W_{cl} + W_{mm} \qquad (11)$$
$$L_{gc} = L_{cf} * I_{cf} * W_l \qquad (12)$$

L_{gc}: yearly logistics cost ($)

$$O_{sc} = N_y * (Y_{osc} + L_{gc}) \qquad (13)$$

O_{sc}: total life cycle operations and support ($)
N_y: life cycle of station (yrs.)
Y_{osc}: ground operations and support cost, as above $80M/year ($)

$$\text{Total Investment} = S_c + L_c + O_{sc} \qquad (14)$$

Results

Please refer to the figure below for the graph of results.

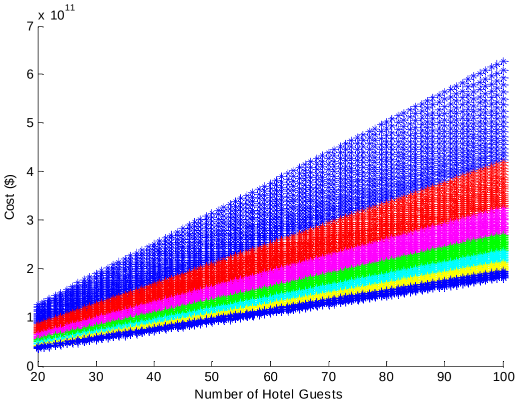

Figure 10 Cost vs. number of Space Hotel guests

In Figure 10, the different colors represent different durations of stay in increments of 20 days starting from the minimum of 30 days up to 170 days. The colors closer to the bottom of the graph represent long durations of stay. Here a trade was conducted in which the weight of the Space Hotel is calculated for the number of guests and duration and then cost is estimated based the above factors plus the weight of Space Hotel.

It can be seen in Figure 10 that the cost estimation is linear. This prevents any sort of minimization of the cost of building, launching, assembling, and running a Space Hotel. However, it can be seen that a Space Hotel business model which is designed around fewer guests staying for longer durations is a way to keep costs low.

Conclusion

A conceptual design for a Space Hotel was created and software was written to estimate the cost required to build, launch, assemble, and run the hotel. These costs were estimated based upon mass estimates for structure and environmental control systems required to support human life onboard the Space Hotel.

If we examine Figure 10, we notice that as duration of stay increases, costs decrease. This can be seen because the colored sections on the plot at the bottom are the longer guest stay durations. This makes sense because this lowers the logistical cost of shuttling people to and from the Space Hotel. Launches become prohibitively expensive if there are large numbers of guests and that are staying for short durations. As the number of guests increases, the smaller duration have a large effect on the cost. However, if the duration of stay is large, then duration has a smaller effect on costs because construction and ground support costs dominate. With long durations, it is possible to keep a large number of guests in space with a relatively small change in costs.

If one were looking to profit from this type of venture, it would be beneficial to require stays of up to 6 months and have 100 guests. The costs would be lower by a long duration and large revenues could possibly be seen due to the large number of guests staying at the hotel.

Future Work

A major area for future work would be to create a more detailed cost model for the Space Hotel. This enhanced cost model may result in a nonlinear distribution of costs, unlike the results shown in Figure 10. This may yield a minimum cost design for the Space Hotel.

In addition, a more detailed structural design of the Space Hotel could be created which would yield a more accurate mass estimate of the structure.

Appendix A: MATLAB source code

structure.m

```
% William Nadir
% 16.851 Satellite Engineering
% Problem Set 5
%
% Space Hotel Structural Design Software Module
%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%
% INPUTS
%
% N_guests  = Number of people staying on board the Space Hotel at any time
% duration  = Duration of stay for guests of the Space Hotel (days)
%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%
% OUTPUTS
%
% str_mass  = Mass estimate of structure of Space Hotel (kg)
% spin_rate = Spin rate of hotel to produce artificial gravity in
%             habitation modules (m/s)
%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%

function [str_mass,spin_rate] = structure(N_guests, duration)

% Here the volume required per passenger onboard the hotel is determined
time        = [2 30 60]; % duration of stay (days)
req_volume  = [150 780 1800]; % required "free volume" per passenger (ft^3)

if duration <= time(1)
    vol = req_volume(1);
elseif duration > time(1) && duration < time(2)
    vol = interp1(time,req_volume,duration,'linear');
elseif duration == time(2)
    vol = req_volume(2);
elseif duration > time(2) && duration < time(3)
    vol = interp1(time,req_volume,duration,'linear');
elseif duration == time(3)
    vol = req_volume(3);
end

% Input habitation module volume here
hab_free_volume = 4500; % (ft^3)

% Calculate how much free volume is required for the hotel guests
total_free_vol = N_guests * vol; % (ft^3)

% Determine how many habitation modules are required to house all the
% guests (rounding up)
N_habs = ceil(total_free_vol / hab_free_volume);
```

```
% Here we determine the mass of each hotel component
bulkhead_thickness = .4; % (in)
rho = .103; % Al 2219 (lb/in^3)

% Habitation modules
hab_dia     = 170; % (in)
hab_length  = 500; % (in)
node_dia    = 96;  % Nodes at the ends of each habitation module (in)

hab_mass = rho * hab_length * pi * (((hab_dia/2)^2) - ...
        (((hab_dia - 2*bulkhead_thickness)/2)^2));

% Here the mass for welds (1%) and internal structure (10%) are added
hab_mass = hab_mass + (hab_mass * .01) + (hab_mass * .1);

% Here the Whipple Shield mass is determined (radius is 4.2" larger than
% module)
whipple_density     = .0975; % Al 6061 (lb/in^3)
whipple_thk         = .08; % (in)
whipple_mass_hab    = whipple_density * hab_length * pi * ...
                ((((hab_dia/2) + 4.2)^2) - ...
                ((((hab_dia - 2*whipple_thk)/2) + 4.2)^2));

% Final habitation module mass plus 1.5 factor since calculations are very
% rough
hab_mass = (hab_mass + whipple_mass_hab)* 1.5; % (lb)

% Determine dimensions of overall hotel structure
% Assume that the circumference of the habitation module ring is roughly
% equivalent to the sum of the lengths of the habitation modules
hotel_dia = (N_habs * (hab_length + node_dia)) / pi; % (in)

% Interconnecting cylidrical structural elements
ic_dia      = 48; % (in)

% Assume the lengths of the interconnecting tubes is roughly equivalent to
% the radius of the hotel ring
ic_length   = hotel_dia / 2; % (in)

ic_mass = rho * ic_length * pi * (((ic_dia/2)^2) - ...
        (((ic_dia - 2*bulkhead_thickness)/2)^2));

% Here the mass for welds (1%) and internal structure (10%) are added
ic_mass = (ic_mass * .01) + (ic_mass * .1);

% Here we determine the Whipple Shield mass for the IC modules
whipple_mass_ic = whipple_density * ic_length * pi * ...
            ((((ic_dia/2) + 4.2)^2) - ...
            ((((ic_dia - 2*whipple_thk)/2) + 4.2)^2));

% Final habitation module mass plus 1.5 factor since calculations are very
% rough
ic_mass = (ic_mass + whipple_mass_ic)* 1.5;

% Here we assume the center cylinder mass is equivalent to that of a habitation
% module
center_module_mass = hab_mass; % (lb)
```

```
% Here the total structural mass is calculated (lb)
str_mass = (hab_mass * N_habs) + (ic_mass * N_habs) + center_module_mass;

% Convert to kilograms from pounds
str_mass = str_mass * .454;  % (kg)

% Determine spin rate required to produce artificial gravity in habitation
% modules
g = 32.2; % (ft/s^2)
spin_rate = sqrt(g * (hotel_dia/2)); % (ft/s)

% Convert to meters/sec
spin_rate = spin_rate * .3048;  % (m/s)
```

cost_model.m

```
% Christopher Hynes
% 16.851 Satellite Engineering
% Problem Set 5
%
% Space Hotel Cost Software Module
%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%
% INPUTS
%
% years  = number of years in operation
% n_crew = Number of people staying on board the Space Hotel at any time
% duration  = Duration of stay for guests of the Space Hotel (days)
% w_f = weight of structure (kgs)
%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%
% OUTPUTS
%
% total_cost = amount (dollars) of total investment required for
% construction, logistics, and operation
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%
function total_cost = cost_model(years, n_crew, duration, w_f)

%Please see paper for explanations
s_cf = 104e3; %space segment cost factor [$/kg]
p_cf = 1.0; %
r_cf = 2.0; % research and development cost factor

s_c = s_cf*p_cf*r_cf; %space cost

l_cf = 15.2e3; %launch cost factor
i_cf = 1.33; %insurance cost factor

l_c = l_cf*i_cf*w_f; %launch cost

y_osc = 80e6; %yearly operation cost

delta_cs = 2000; %crew support specific weight [kg/person]
```

```
delta_crew = 170; %crew specific weight [kg/person]
delta_gear = 72; %crew specific gear weight [kg/person]

consumption_rate = 9.453515; %rate of consumption [kg/person]

w_cl = 365*((delta_cs + delta_crew + delta_gear)*(n_crew/duration) + consumption_rate*n_crew);  %yearly crew
logistics weight

m_mf = 0.01; %maintenance materials weight fraction

w_mm = w_f*m_mf; %materials yearly delivery weight

w_l = w_cl + w_mm; %logistics weight
l_gc = l_cf*i_cf*w_l; %logistics cost (per year)

o_sc = years*(y_osc + l_gc);  % operational cost

total_cost = s_c + l_c + o_sc;
```

cost_modeltest.m

```
% Christopher Hynes
% 16.851 Satellite Engineering
% Problem Set 5
%
% Space Hotel Cost Software Module
%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%
% INPUTS
%
% years  = number of years in operation
% n_crew = Number of people staying on board the Space Hotel at any time
% duration  = Duration of stay for guests of the Space Hotel (days)
% w_f = weight of structure (kgs)
%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%
% OUTPUTS
%
% total_cost = amount (dollars) of total investment required for
% construction, logistics, and operation
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%
% function total_cost = cost_model(years, n_crew, duration, w_f)

N_guests_min = 20;
N_guests_max = 100;
duration_min = 30;
duration_max = 180;

cost_matrix = zeros(N_guests_max - N_guests_min + 1, duration_max - duration_min + 1);

for N_guests = N_guests_min:N_guests_max
    for duration = duration_min:duration_max

        [str_mass,spin_rate] = structure(N_guests, duration);
        total_cost = cost_model(10, N_guests, duration, str_mass);
```

```
        cost_matrix(N_guests - N_guests_min + 1,duration - duration_min + 1) = total_cost;
    end
end

figure(1)
for i = 1:duration - duration_min + 1
    hold on
    duration = duration_min + i;
    if duration < 30
        plot([N_guests_min:N_guests_max],cost_matrix(:,i),'k*');
    elseif duration >= 30 && duration < 50
        plot([N_guests_min:N_guests_max],cost_matrix(:,i),'b*');
    elseif duration >=50 && duration < 70
        plot([N_guests_min:N_guests_max],cost_matrix(:,i),'r*');
    elseif duration >=70 && duration < 90
        plot([N_guests_min:N_guests_max],cost_matrix(:,i),'m*');
    elseif duration >= 90 && duration < 110
        plot([N_guests_min:N_guests_max],cost_matrix(:,i),'g*');
    elseif duration >= 110 && duration < 130
        plot([N_guests_min:N_guests_max],cost_matrix(:,i),'c*');
    elseif duration >= 130 && duration <= 150
        plot([N_guests_min:N_guests_max],cost_matrix(:,i),'y*');
    elseif duration >= 150 && duration <= 170
        plot([N_guests_min:N_guests_max],cost_matrix(:,i),'b*');
    end
end
ylabel('Cost ($)')
xlabel('Number of Hotel Guests')
```

References

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