A SPACE TOURISM PLATFORM MODEL FOR ENGINEERING AND ECONOMIC FEASIBILITY

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Abstract

A concept-level model is presented that produces technical design parameters and economic feasibility information for Space Tourism platforms. A Space Tourism platform is defined as a space-station-like vehicle which is designed to sustain humans in space for long durations. Such platforms could be placed in Earth orbit, around the Moon, at a stable Earth-Moon libration point, around Mars, or wherever it is desired to host a platform for Space Tourism.

One key problem in making Space Tourism feasible is making sure that it is cost effective. A method is developed which creates an engineering model based upon desired mission requirements, then links it to a cost model. The cost model is unique in that it is designed for commercial viability rather than for government-run programs. The cost attained is a life-cycle cost from which you can determine economic variables such as rates of return, initial investment, and time to return on initial investment. Using such a model it is possible to determine the trade between number of tourists and the price to charge them.

The development of the analytical tool employed an approach that accommodated possible payloads characterized as simplified parameters such as power, weight, volume, crew size, and endurance. In creating the approach, basic principles are employed and combined with parametric estimates as necessary. Key system parameters are identified in conjunction with overall system design. Typical ranges for these key parameters are provided based on empirical data extracted from actual human spaceflight systems.

Sample Space Tourism Platforms are presented with emphasis on maximizing rate of return through variance of key mission requirements and ticket prices. This paper is based on work Dr. Reynerson recently completed at George Washington University in fulfillment for the degree of Doctor of Science in Astronautics.

Introduction

A space business park is a commercially run multi-use space facility designed for use by a wide variety of customers. Examples of commercial use may include biological and materials research, processing, and production, space tourism habitats, and satellite maintenance and resupply depot. The Commercial Space Transportation Study (CSTS) conducted by several major aerospace contractors for NASA in May 1994 concluded that this sort of space facility has high market potential if space transportation costs can be reduced. In the CSTS it was recommended that further analysis be performed to develop a more complete preliminary design of a commercially procured space business park.

This paper is based upon work completed for the degree of Doctor of Science in Astronautics at the George Washington University. It was the goal of this research to develop a design methodology and an analytical tool to assist in creating feasible preliminary design information for space business parks. The design tool was validated against a number of real facility designs. Appropriate model variables were adjusted to ensure statistical approximations would be valid for subsequent analyses. The tool was used to analyze the effect of various requirements on the size, weight and power of the facility and its subsystems.

The approach for the analytical tool was to input potential payloads as simple requirements, such as size, weight, power, crew size, and endurance. In creating the theory, basic principles were primarily used and combined with parametric estimation of data when necessary. Key system parameters were identified for overall system design. Typical ranges for these key parameters were identified based on real human spaceflight systems.

A rough cost model was used to estimate potential return on investments, initial investment requirements and number of years to return on the initial investment. For this paper a multi-use facility example is used to evaluate the effect of launch cost on the entire life cycle cost and profitability of the facility. The cost model factors in logistics cost for the delivery of crew and supplies to the facility as well as the prices imposed on the customers.

Multi-use Space Facilities

Many potential markets exist for a space business park. The Commercial Space Transportation Study (CSTS) was conducted by six aerospace companies to identify promising markets for commercial space transportation that could be enabled by reducing transportation costs. The results of this study was used as inputs for the Commercial Space Business Park Study (CSBPS) conducted by Boeing under contract to NASA and completed in April 1997. Some of these markets were selected for case studies in the CSBPS representing a diverse spectrum of potential uses. Case studies selected include protein crystal growth and cell culturing, satellite repair and servicing, movie/TV/advertising studio, and bed and breakfast hotel.

Engineering Math Model Governing Equations

The inputs to the model are the following variables:

$W_p =$ payload power (payload being defined as space rated hardware and equipment used to create revenue for the space business park)
$V_p =$ payload volume
$P_p =$ payload user power (most commonly referred to as user power on space stations)
$N_c =$ number of crew members
$E_c =$ designed endurance limit for the crew. This time factor will also be the assumed resupply interval for consumables calculations.

Assume the outputs to our model are the following variables:

$W_f =$ facility weight
$V_f =$ facility volume
$P_f =$ facility power

Assume that the output variables are some linear combination of the input variables. In reality the input variables may be raised to some arbitrary power as follows.

$$
\begin{aligned}
W_f &= f(W_p, V_p, P_p, N_c, E_c) = a \cdot W_p^a + b \cdot V_p^b + c \cdot P_p^c + d \cdot N_c^d + e \cdot E_c^e \\
V_f &= g(W_p, V_p, P_p, N_c, E_c) = f \cdot W_p^f + j \cdot V_p^g + g \cdot P_p^h + h \cdot N_c^i + i \cdot E_c^j \\
P_f &= h(W_p, V_p, P_p, N_c, E_c) = k \cdot W_p^k + l \cdot V_p^l + m \cdot P_p^m + n \cdot N_c^n + o \cdot E_c^o
\end{aligned}
\tag{1 - 3}
$$

If a linearized form of equations 1 through 3 are used then the following approximations can be made:

$$
\begin{aligned}
W_f &\cong a \cdot W_p + b \cdot V_p + c \cdot P_p + d \cdot N_c + e \cdot E_c \\
V_f &\cong f \cdot W_p + j \cdot V_p + g \cdot P_p + h \cdot N_c + i \cdot E_c \\
P_f &\cong k \cdot W_p + l \cdot V_p + m \cdot P_p + n \cdot N_c + o \cdot E_c
\end{aligned}
\tag{4 - 6}
$$

In matrix form:

$$
f = \mathrm{A} \cdot p \quad \text{where} \quad f = \begin{pmatrix} W_f \\ V_f \\ P_f \end{pmatrix},
$$

$$
\mathrm{A} = \begin{bmatrix} a & b & c & d & e \\ f & j & g & h & i \\ k & l & m & n & o \end{bmatrix}, \text{ and}
$$

$$
p = \begin{pmatrix} W_p \\ V_p \\ P_p \\ N_c \\ E_c \end{pmatrix} \tag{7}
$$

The above equations form the basis for the engineering concept model. Details of this model and its validation are beyond the scope of this paper but can be found in reference [4].[1]

Cost Model

A cost model was created to complement the engineering model. For a commercial development cost tends to be the bottom line and

[1] Reynerson, Chapter 4.

therefore should be addressed. 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 model consists of two main sections: required investments and revenues. The required investment areas addressed include the space segment, launch vehicles, operations, and logistics. The revenues considered include crew and user payload related revenues.

Space Segment Cost

The space segment is modeled using the product of four variables. The space segment cost factor (Scf) is the price per kg of facility on orbit. This value typically varies from 58 to 148 $K/kg for unmanned spacecraft.[2] For manned space programs (Note that these values are for government run programs) the range is 38 to 157 $K/kg and the mean is 104 $K/kg. The program cost (Pcf) is normalized over the number of manned vehicles produced. The low number in the Skylab program is likely due to less research and development required since it was derived from the Apollo program.

The research, test, development, and engineering (RTD&E) cost factor (Rcf) is used to compensate for new development cost. RTD&E cost tends to be about three times that of the TFU cost. For manned systems this would make the Scf range from 22 to 52 $K/kg for the TFU if you assume all of the programs were pure RTD&E cost (not including Skylab). Assuming this range for the TFU, then the Rcf should be 3 for new development programs, 1 for a program based on existing hardware, or somewhere in between if there is partial development required.

The space segment cost (Sc) can now be defined by the following equation:

$$S_c = S_{cf} \cdot P_{cf} \cdot R_{cf} \cdot W_f \qquad (10)$$

Launch Vehicle Cost

The launch cost factor (Lcf) can be estimated using historical data and planned cost goals for future developments. Launch vehicle costs[3] for several competing launch systems range from 4.4 to 57.4 $K/kg. The average cost is around 15.2 $K/kg.

An insurance cost factor (Icf) is used to account for insurance cost related to launch. Typically for commercial launches, insurance runs about one third of the launch cost. The Icf would therefore be a value of around 1.33.

The launch cost (Lc) for delivering the facility to orbit can now be defined by the following equation:

$$L_c = L_{cf} \cdot I_{cf} \cdot W_f \qquad (11)$$

Ground Operations and Support

The cost for the ground equipment is typically much smaller than the cost needed for the space segment and launch. But the operations for the ground stations becomes significant over time and should be considered in the cash flow calculations to counter the yearly revenues. Operations, mission, and program support costs for the Skylab program[4] average (over 4 years) $31.6 M in 1970's dollars. This cost is roughly $83M in 1997. The International Space Station program has $13B in its operations budget over 10 years for an average of $1.3B per year.[5] This figure likely includes logistics costs for delivery of consumables and maintenance costs to upkeep the facility over its ten-year design life. It may also include the RDT&E for future payloads, experiments, and support. For the purposes of this ROM cost model, a figure of $80M per year is used for yearly operations and support costs (Yosc). A ten-year operational period (Ny) is assumed for life cycle costing purposes.

Logistics

To account for the delivery of people, payloads, consumables, and products to and from the facility, a yearly logistics cost is calculated based on weight delivered and launch cost. A logistics crew specific weight (d_{cs}) is defined as the equipment weight needed for crew support during the trip to and from orbit. This value should be no more than the crew specific weight for space facilities due to much shorter duration on orbit. The value for crew specific weight can be estimated from previous manned missions (1500 kg/person for

[2] Wertz, SMAD, pp 735, table 20-14.
[3] Space Business News, February 5, 1997, pp 3.
[4] Ezell, pp 62-69.
[5] International Space Station Fact Book.

Mercury to 11030 kg/person for Apollo). The Apollo crew specific weight is high due to the stressing requirements to go to the moon. The Space Shuttle crew specific weight is high due to its design to accommodate a heavy lift payload.

For this cost model a nominal value of 2000 kg/person is assumed for logistics crew specific weight, which is just higher than a Gemini capsule. Equation 12 defines the yearly crew logistics weight (Wcl) including consumables. This model assumes resupply intervals to be that of the endurance interval, Ec.

$$W_{cl} = 365 \cdot \left((d_{cs} + d_{crew} + d_{cg}) \cdot \frac{N_c}{E_c} + e \right) \tag{12}$$

Here d_{crew} and d_{cg} are the crew system specific weights for the crew itself and their gear, respectively. e is the consumable consumption rate for the entire facility.

For user payload logistics, a yearly turnover fraction (Tf) is defined as that fraction of total payload weight that is replaced during the year. If the payload requires a certain amount of production materials delivered, then a materials weight fraction (Mf) is used. The Mf is defined as that fraction of equivalent payload weight is required per year for payload production needs. The value for Mf is highly dependent upon the payload mission. For a tourism mission it might be zero and for a materials processing facility it could be more than 100%. The value for Mf is also mission dependent and very much market driven. If payloads have a nominal life of 5 years, then the turnover rate would be 100% in ten years. Therefore the yearly turnover rate would average 10%. The yearly user payloads logistics weight (Wupl) is then defined by the following:

$$W_{upl} = W_p \cdot \left(M_f + T_f \right) \tag{13}$$

To account for maintenance materials required for the facility, a maintenance materials weight fraction (Mmf) is established. The Mmf is that fraction of the facility weight that is required to be replaced each year. A nominal value of Mmf = 0.01 is assumed for this model. The maintenance materials yearly delivery weight (Wmm) is therefore:

$$W_{mm} = W_f \cdot M_{mf} \tag{14}$$

The total yearly logistics weight is the sum of equations 12, 13, and 14 as follows:

$$W_l = W_{cl} + W_{upl} + W_{mm} \tag{15}$$

The yearly logistics cost is similar to equation 11 but based on logistics weight:

$$L_{gc} = L_{cf} \cdot I_{cf} \cdot W_l \tag{16}$$

The total life cycle operations and support cost (Osc) including ground and logistics is then:

$$O_{sc} = N_y \cdot \left(Y_{osc} + L_{gc} \right) \tag{17}$$

The total investment required over the facility life is then:

$$TI = S_c + L_c + O_{sc} \tag{18}$$

Space Hotel Examples

Performance Driven Example

For the following space hotel examples 46 passengers and 4 non-paying crew members is selected for cost analysis. No extra user payloads are assumed to be onboard. Cost is assumed to be $1M per day per person for the stay.

Figure 1 shows return on investment given the performance requirements stated above. The price for launch and return per person is plotted for $2.5 M, $5 M, $10 M, and $15 M. The trip duration is varied from 0 to 60 days. In general, the rate of return increases as trip duration increases. Short duration trips of less than 20 days need to have sufficient pricing on launch and return to ensure profitability.

Figure 2 shows number of years to return on initial investment. For trips of duration of 20 days or more the number of years for the return is reasonable at less than 4 years. For launch and return prices of $5 M and less the number of years to return is greater than the operational life when trip durations are short.

Cost Driven Example

This example is based on forcing the engineering design to be driven by initial investment cost. Both the engineering and cost models above were combined to create the cost constrained design. The cost constraint selected is an initial investment of $5 B. Figure 4 shows the facility weight corresponding to initial investment amount. For an initial investment of $5 B the facility weight is roughly 130600 kg. This corresponds to no more than nine persons supported in the hotel. To calculate investment returns, assume in this case that there are two crew members that are hired and will not be paying for the trip and stay.

Figure 3 shows the initial investment required, which includes the space segment and launch costs. The range is from $25.4 billion to $26.6 billion depending on the duration of stay.

Figure 5 shows return on investment for the cost driven example. Compared to Figure 1, the endurance threshold to ensure profitability must be raised by about five days. The maximum return on investment decreases from about 150% to 100%.

Figure 6 shows number of years to return on initial investment. As compared to Figure 2 trip durations must be greater than 35 days to ensure the number of years to return is less than four for the cheapest launch and return price.

Conclusions

This paper has shown the basic governing equations for both an engineering and cost model that can be used for multi-use space facilities. Although the cost model used is rough and not absolute, it can show the relative effect of various payloads and facility designs. The power of combining both engineering and cost models can effectively show the impact of payload requirements on cost. Alternatively, this combination can show the amount of payloads you can support given a limit on the initial investment amount. Such trades are critical during the concept design phase for space facilities. For a commercially developed and operated facility such trades are mandatory in providing a business case based upon sound engineering and cost data

References

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3. National Aeronautics and Space Administration, “International Space Station Fact Book”, January 1997, information also found in an internet website: http://station.nasa.gov/reference/factbook.

4. Reynerson, C. M., “Concept Design Theory And Model For Multi-Use Space Facilities: Analysis Of Key System Design Parameters Through Variance Of Mission Requirements”, D. Sc. dissertation, George Washington University, 1997.

5. Wertz, J. R., Larson, W. J., “Space Mission Analysis and Design (SMAD)” , 2nd Edition, Microcosm Press, 1992.

6. Willenberg, H. J., Hopkins, J., Rubeck, M., Torre, L., Lauer, C., Woodcock, G. R., , “Commercial Space Business Parks, Final Report of Task Order # TOF-021 to Contract #NAS8-50000”, Boeing Defense and Space Group, Final Briefing, 7 April 1997.

Figure 1 Performance Driven Model Results for Space Hotel: Return on Investment

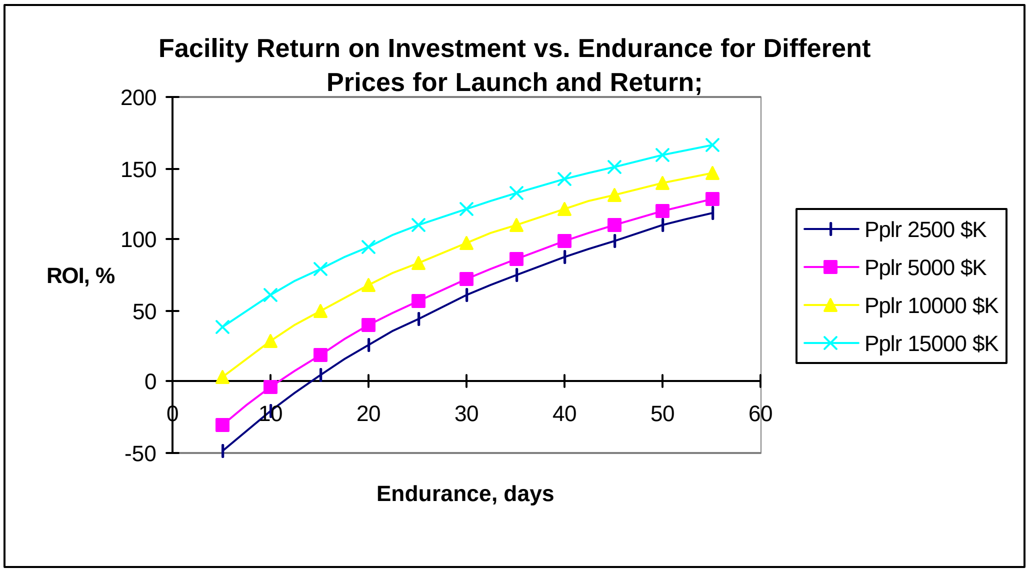

Figure 2 Performance Driven Model Results for Space Hotel: Number of Years to Return on Initial Investment

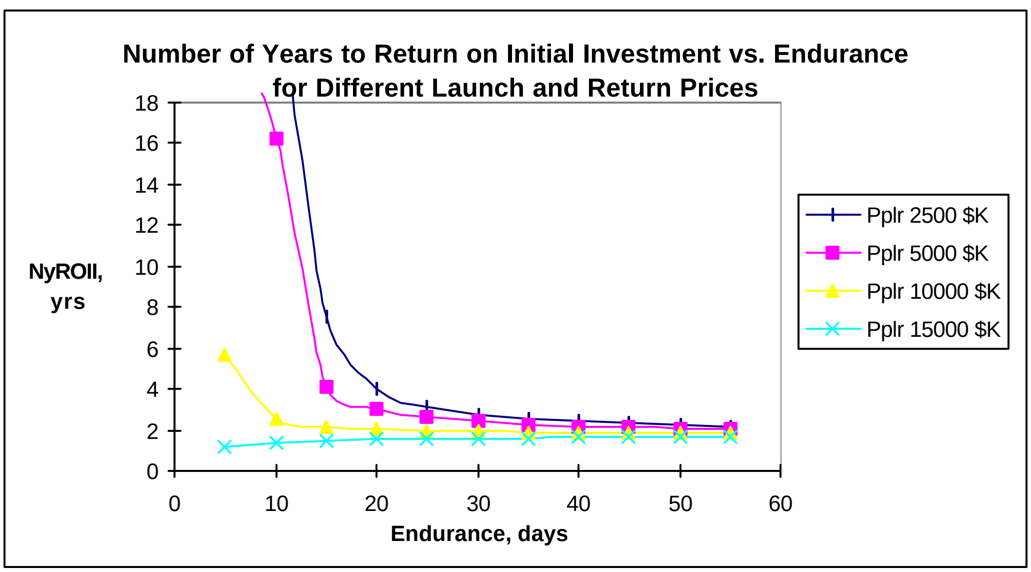

Figure 3 Performance Driven Model Results for Space Hotel: Initial Investment

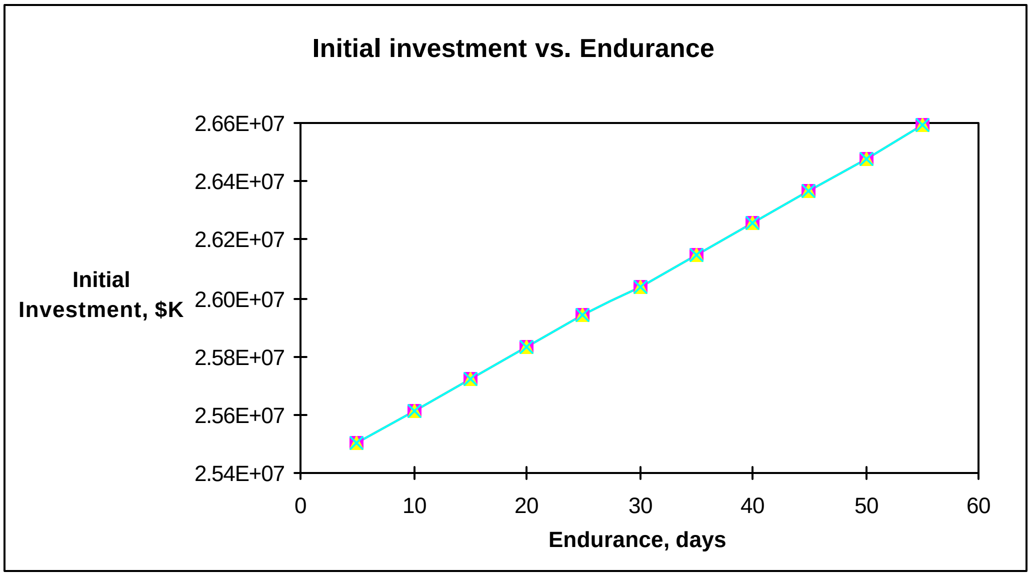

Figure 4 Initial Investment for Space Hotel - Cost Driven Model Results

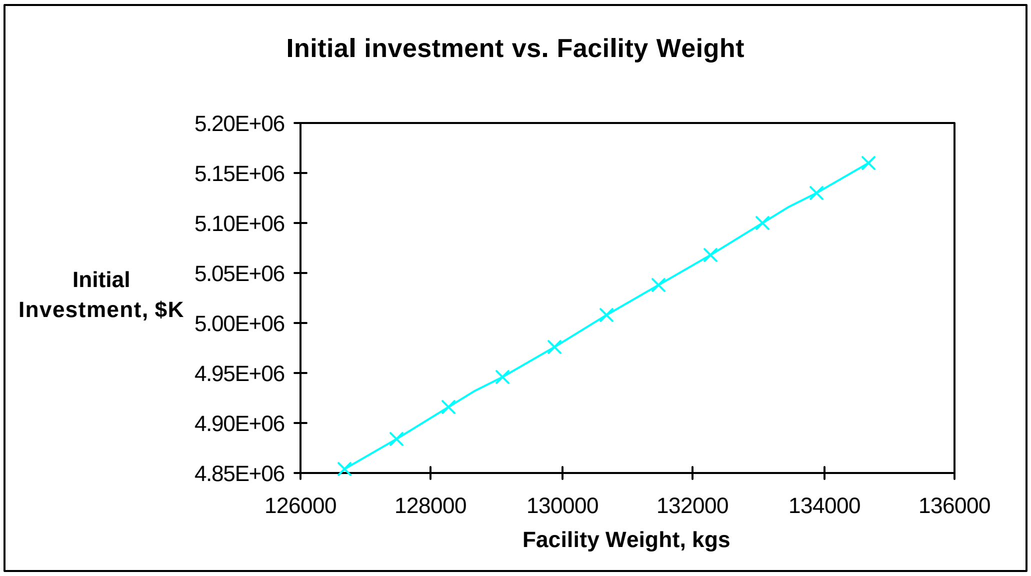

Figure 5 Cost Driven Model Results for Space Hotel: Return on Investment

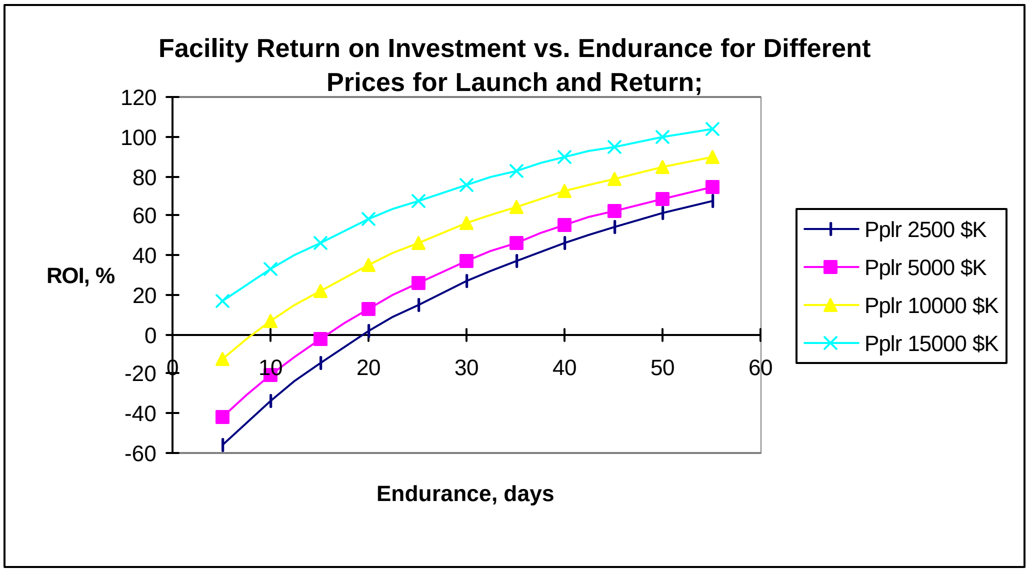

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Figure 6 Cost Driven Model Results for Space Hotel: Number of Years to Return on Initial Investment