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Impact of Subsystem Reliability on Satellite Revenue Generation and Present Value

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A new framework is developed that analytically links an engineering concept, a system's reliability, with both managerial and financial concepts, the system's revenue generation capability, and its present value. A communications satellite is used as an example to illustrate the use and insights that can be generated from this framework. For instance, after the development of a revenue model for a communications satellite, the cost of unreliability was quantified: the present value penalty for the lack of 100% payload reliability. Next, the value of redundancy was also analytically captured: the satellite incremental present value provided by payload redundancy. The central finding is that present value calculations of a technical revenue-generating system, in this instance, a communications satellite, that do not account for system's reliability overestimate the system's present value and, thus, can lead to flawed investment decisions. Finally, when sensitivity analysis is performed on the various drivers of the satellite present value, it was found, against conventional wisdom, that redundancy in communications satellite payload is overrated; in other words, that increasing payload redundancy provides limited incremental value to the spacecraft.

Nomenclature

$F(t)$	=	probability distribution function that item fails within time interval [0; t]
$L(t)$	=	satellite load factor as function of time, number of transponders in use at time t divided by total number of transponders onboard spacecraft; also known as utilization factor
L_0	=	average load factor of all current geostationary orbit communications satellites, approximately 60% in 2003
P_i	=	price of transponder i per unit time
$\langle P_{Tx}(t)\rangle$	=	average price of transponder onboard spacecraft per unit time
R_n	=	reliability of item at time $n\Delta T$
$R(t)$	=	reliability of item
$r_{\Delta T}$	=	discount rate adjusted for time period ΔT
T_f	=	random variable, time to failure of item
Tx_{total}	=	total number of transponders onboard spacecraft
$t_{\text{wear-out}}$	=	beginning of wear-out period of item
$\hat{u}_i$	=	expected revenues generated between $(i-1)\Delta T$ and $i\Delta T$
$u(t)$	=	expected revenue model of spacecraft per unit time, or system's utility rate after it reaches operational capability
ΔT	=	time period, small enough over which it is appropriate to consider $u(t)$ and $\lambda(t)$ constant
$\lambda(t)$	=	failure rate of item
τ	=	fill rate time constant

I. Introduction

RELIABILITY studies are always conducted to provide information for stakeholders as a basis for decisions. Relevant data needed as input, and the technique(s) to be used, are often dependent on the decision problem at hand.[1] It is, therefore, good practice, before a reliability study is conducted, to specify clearly the decision problem at hand.

Whereas most studies in the reliability literature provide either an assessment/prediction of the reliability of a complex engineering system, a comparison of a predicted vs observed system's reliability, or methods for designing for reliability, this paper has quite different objectives. In this paper, we explore the impact of a commercial satellite and its subsystems' reliabilities on its revenue generating capability. To do so, we first develop a revenue model for a communications satellite. We then integrate these results and compute an expected present value of the satellite as a function of its design lifetime. Finally, we identify and discuss the spacecraft value levers from a operator's point of view. The three concepts we relate in this paper are reliability R_i, revenue generation capability $u(t)$, and the system's present value. This triad is shown in Fig. 1.

II. Satellite Revenue Model: Case of Fixed Satellite Services Geostationary Orbit Communication Satellite

In this section, we focus our attention on spacecraft revenue or a utility model as a function of time. We are interested in forecasting the revenue profile of a spacecraft, $u(t)$, after it reaches operational capability. We refer to $u(t)$ as the expected revenue model of a system per unit of time, in the case of a commercial venture, or the system's utility rate model, in the case of a scientific or military endeavor.

When we set up to investigate communications satellite revenues, we were surprised to find that, although numerous spacecraft cost models exist and are widely available and are used and taught in academic environments, no spacecraft revenue models exist in the literature. The data required to build these models are not easy to access (tracking the revenue of an individual satellite on a monthly basis, along with its utilization rate and service offered). In addition, one can presume that satellite operators are not necessarily eager to share this financial information.

In the following text, we develop a simple revenue model for a fixed satellite services (FSS) satellite. We do not consider direct broadcast services satellites for which the concept of transponder as traditionally defined and used in Eq. (1) breaks down. The purpose of this revenue model is merely to illustrate the results that can be

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obtained using the analytic framework developed in the following section. Other types of spacecraft revenue models, if available, could have been used with equal effectiveness.

For an FSS geostationary orbit (GEO) communications satellite, the revenue model $u(t)$ can be expressed as follows:

$$u(t) = \sum_i (Tx_{i;t} \times P_i) \tag{1}$$

where

$$\sum_i (Tx_{i,t})$$

is the sum of all transponders onboard the spacecraft that are active/leased at time t.

In other words, Eq. (1) simply states that the revenues at a particular point in time are equal to the sum of the revenues generated by each transponder active at that time. However, the lease price of each transponder in use at one time need not be homogeneous, hence, our use of an indexed price P_i per transponder at time t. Indeed, the lease price of a transponder, or, equivalently, the revenues generated by a transponder for the satellite operator, varies based on the leased bandwidth, on the duration of the contract and on the satellite operators offering discounts on transponder price based on duration of lease and capacity.

We define the average lease price of a transponder onboard a spacecraft at time t as follows:

$$\langle P_{Tx}(t)\rangle = \frac{\sum_i (Tx_{i,t} \times P_i)}{\sum_i (Tx_{i,t})} \tag{2}$$

The satellite load factor at one particular point in time is equal to the total number of transponders in use at time t divided by the total number of transponders onboard a spacecraft. It is defined as follows:

$$L(t) = \frac{\sum_i (Tx_{i,t})}{Tx_{\text{total}}} \tag{3}$$

Tx_{total} is the total number of transponders onboard a spacecraft. Incorporating Eqs. (2) and (3) into Eq. (1), we develop the following expression for the expected revenue model of a communications satellite per unit time:

$$u(t) = \langle P_{Tx}(t)\rangle \times Tx_{\text{total}} \times L(t) \tag{4}$$

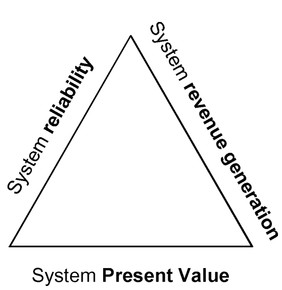

Fig. 1 Three concepts related in this paper: system's reliability, revenue generation, and present value.

Point values for transponder price (by region and frequency band) are available publicly. For example, the average yearly price of a transponder in North America as of June 2002 is \$2.1 million in Ku-band and \$1.8 million in C-band. These transponder point values are good proxies for our average price of a transponder $\langle P_{Tx}(t)\rangle$. The average yearly price of a transponder has been steadily declining over the years, at approximately 4% per year, due to increased competition and overcapacity on orbit.

After the spacecraft is launched and reaches operational capability, the operator of the satellite acquires customers for this new on-orbit bandwidth capacity. As new customers are acquired, more transponders are leased, and the spacecraft load factor $L(t)$ increases over the time. Satellites, however, do not get filled to capacity due to an oversupply of on-orbit bandwidths and customer turnover. The current average load factor L_0 for all GEO communications satellites hovers around 60%; this number is among the lowest ever experienced and has traditionally been around 70% (Ref. 2).

We use an exponential fill process, first suggested by Sperber,[3] with a time constant τ, to capture the load factor dynamics of a communications satellite after it has reached operational capability:

$$L(t) = L_0 \times [1 - \exp(-t/\tau)] \tag{5}$$

For the purpose of this paper, we define the three cases for the values of L_0 and τ in Table 1.

Equation (6) represents what we set out to develop in this section, namely, a communications satellite revenue model. We are currently working with industry partners to validate this model. However, the accuracy of this model bears no impact on the framework we develop in this work, nor on our theoretical findings, given the objectives of this paper.

$$u(t) = \langle P_{Tx}(t)\rangle \times Tx_{\text{total}} \times L_0 \times [1 - \exp(-t/\tau)] \tag{6}$$

The worldwide average lease price of a 36-MHz transponder in 2000 was \$1.51 million per year, or \$126,000 per month.[4] In the following text, we use this number as a proxy for $\langle P_{Tx}(t)\rangle$ in Eq. (6).

Assuming a spacecraft with 50 36-MHz transponder equivalents, currently the average size of a GEO communications satellite, and no decrease in the lease price of a transponder over the spacecraft design lifetime, we show in Fig. 2 the cash flows generated by the satellite under the three scenarios defined in Table 1; these cash flows are the solutions of Eq. (6).

We recognize in Fig. 2 the exponential fill of the satellite with the three different time constants defined in Table 1. Also, we note the asymptotic behavior of the curves as $t \gg \tau$; the revenues generated per unit time tend asymptotically toward $L_0 \times Tx_{\text{total}} \times \langle P_{Tx}(t)\rangle$.

When the yearly decrease in the lease price of a 36-MHz transponder is taken into account (Table 2), Eq. (6) yields a different result, illustrated in Fig. 3.

Table 1 Values for spacecraft average load factor and time constant associated with its fill rate

Model parameter	Worst case	Nominal case	Best case
L_0, %	60	70	80
τ, months	12	8	4

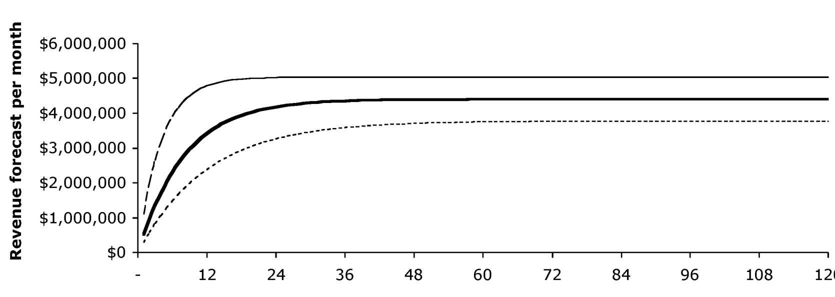

Fig. 2 Communications satellite revenue forecast (50 36-MHz transponder equivalents) under three scenarios defined in Table 1: - - - -, worst forecast; ——, nominal forecast; and – – –, best forecast.

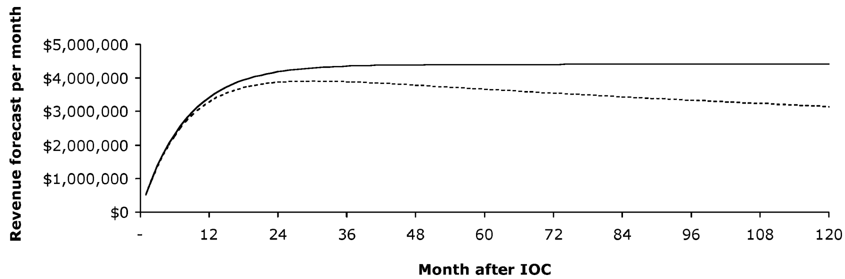

Fig. 3 Communications satellite revenue forecast (50 36-MHz transponder equivalents) under nominal scenario defined in Table 1, with and without yearly decrease in transponder lease price: ——, nominal forecast and - - - -, nominal forecast with 4% per year decrease in *Tx* lease price.

Table 2 Worldwide average lease price per year for a 36-MHz transponder (adapted from Ref. 4)[a]

Year	Lease price, \$, millions
2000	1.51
2001	1.45
2002	1.37
2003	1.32

[a]Compounded annual growth rate 2000–2003, −4.3%.

It is tempting at this point, given the cash flows we have forecasted that the satellite would generate after it has reached operational capability, to use an appropriate discount rate and compute the prevent value of the spacecraft. We will indeed do so in Sec. III after we discuss the impact of the spacecraft reliability on its revenue generation capability.

III. Impact of Satellite Reliability on Its Revenue Generation and Present Value

Reliability, as defined by the International Organization for Standardization ISO 8402, is the ability of an item, component, subsystem, or system, to perform a required function, under given environmental and operational conditions, for a stated period of time. There are, of course, several other definitions of reliability in the literature. In Ref. 1, the authors state that a number of authors prefer the following definition to the ISO 8402: "Reliability is the probability that an item will perform a required function under stated conditions for a stated period of time." These minor differences bear no consequences on our analyses. In the following text, we use a simplified definition of reliability as the probability of an item to survive and remain fully operational between time zero and t.

In this section, we investigate the impact of a system's reliability on its revenue generation capability. We then integrate these results to calculate an expected present value of the system as a function of time. Note that, whereas there are numerous reliability studies in the literature, providing either an assessment/prediction of the reliability of a complex engineering system, or methods for designing for reliability, the analysis in this section is the first to explore and make the connection between reliability, revenue generation capability, and a system's present value. The results are then applied to our communications satellite example.

A. Brief Review of Basic Concepts in Reliability

Reliability concepts are best intuitively introduced through the state of an item and its time to failure. The state of a component with one failure mode, in which the component is either functioning or failed and there are no partial failures, can be described by the state variable $x(t)$:

$$x(t) = \begin{cases} 1 & \text{if component is functioning at time } t \\ 0 & \text{if component has failed at time } t \end{cases}$$

The time to failure T_f of a component is a random variable that describes the time elapsed from when the component becomes operational until it fails for the first time. The relation between $x(t)$ and T_f is shown in Fig. 4.

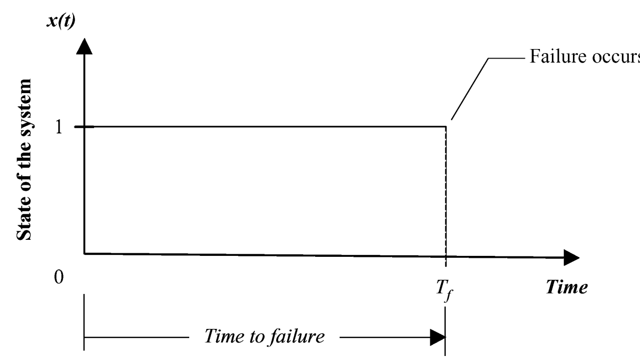

Fig. 4 Relation between state of component and its time to failure (adapted from Ref. 1).

When it is assumed that the time to failure is continuously distributed, the distribution function $F(t)$ represents the probability that the component fails within the time interval $[0; t]$:

$$F(t) = Pr(T_f \leq t) \tag{7}$$

The reliability of a component is the probability that the component has not failed between 0 and t. In other words, the reliability of a component is the probability that the component has survived and is still functioning at time t:

$$R(t) = 1 - F(t) = Pr(T_f > t) \tag{8}$$

The probability density function, which is quite different from the failure rate function, as we will discuss shortly, is the derivative of $F(t)$ and defined mathematically by

$$f(t) = \frac{\mathrm{d}F(t)}{\mathrm{d}t} = \lim_{\Delta t \to 0} \frac{F(t + \Delta t) - F(t)}{\Delta t} = \lim_{\Delta t \to 0} \frac{Pr(t < T_f \leq t + \Delta t)}{\Delta t}$$

$$f(t) = -\frac{\mathrm{d}R(t)}{\mathrm{d}t} \tag{9}$$

The conditional probability that the component will fail between t and Δt when we know that the component is still functioning at time t is given by the following expression:

$$Pr(t < T_f \leq t + \Delta t | T_f > t) = \frac{Pr(t < T_f \leq t + \Delta t)}{Pr(T_f > t)} = \frac{Pr(t < T_f \leq t + \Delta t)}{R(t)} \tag{10}$$

The failure rate of a component, unlike $f(t)$, is the conditional probability density that the component will fail between t and Δt

when we know that the component is still functioning at time t:

$$\lambda(t) = \lim_{\Delta t \to 0} \frac{Pr(t < T_f \leq t + \Delta t | T_f > t)}{\Delta t}$$
$$= \lim_{\Delta t \to 0} \frac{F(t + \Delta t) - F(t)}{\Delta t} \times \frac{1}{R(t)} = \frac{f(t)}{R(t)} \quad (11)$$

Note the difference between the component probability density function given in Eq. (9) and the component failure rate expressed in Eq. (11).

Combining Eqs. (9) and (11), we get

$$\lambda(t) = \frac{f(t)}{R(t)} = -\frac{\mathrm{d}R/\mathrm{d}t}{R(t)} \quad (12)$$

Separating the variables and integrating both sides of the equation gives

$$\lambda \times \mathrm{d}t = -\frac{\mathrm{d}R}{R} \Rightarrow -\int_0^t \lambda(\alpha) \times \mathrm{d}\alpha = \int_1^{R(t)} \frac{\mathrm{d}R}{R}$$
$$\Rightarrow -\int_0^t \lambda(\alpha) \times \mathrm{d}\alpha = \ell\mathrm{n}[R(t)] \quad (13)$$

We finally obtain the general expression of the reliability of a component as a function of its failure rate:

$$R(t) = \exp\left[-\int_0^t \lambda(\alpha) \times \mathrm{d}\alpha\right] \quad (14)$$

Equation (14) is independent of the variation of the component's failure rate over time. When λ is considered constant, that is, the component does not age, Eq. (14) becomes the reliability expression of a component that is, perhaps, more familiar to the practitioner:

$$R(t) = e^{-\lambda t} \quad (15)$$

The failure rate of a component often has the form shown in Fig. 5 and is often referred to as the "bathtub curve."

The failure rate is initially high after the component/product becomes operational. This initial time interval is often referred to as the infant mortality or burn-in period and is explained by the fact that there are undiscovered defects that only appear when components/products are put into service. After these defects are screened out, the components/products that survive this infant mortality period find their failure rate stabilizing at some relatively constant level. As the components/products begin to wear out, the failure rate increases rapidly with time; this is known as the wear-out period.[1,5]

For space components, the infant mortality period is almost eliminated by extensive testing before the component is actually qualified to fly in space and delivered to the user or the satellite manufacturer. A study conducted by The Aerospace Corporation found that 98% of satellites survive infant mortality.[6] Although it is not possible to infer directly from this system-level measure what is happening at the component level, it is nevertheless a good indication that the system's components (less the redundancy) have survived infant mortality as well. Although we initially neglected the transponder infant mortality period in our analysis, and used a constant failure rate model followed by a wear-out period, an anonymous reviewer of a first version of this work provided, among a series of very useful comments, the information that the transponder "first year rate of failure, over a long period of time, has averaged over two to three times the failure rate in the flat part of the bath-tub curve." We consequently incorporated this information into our failure rate model; it is further discussed in the spacecraft example hereafter.

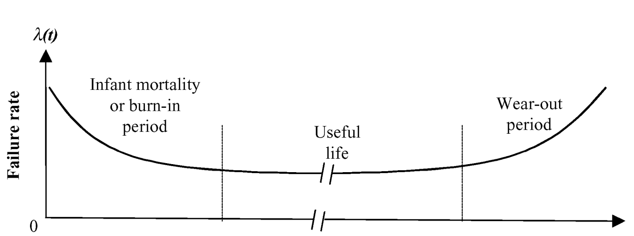

Fig. 5 Failure rate of component as function of time: bathtub curve and three periods of operations (adapted from Ref. 5).

B. Reliability, Revenue Generation, and Present Value

This section, to the best knowledge of the authors, represents a novel contribution to the field of reliability analysis and connects an engineering concept, the reliability of a system, to a financial valuation concept, the present value of a system.

We begin by considering the simple case of a system that can generate $u(t)$ dollars per unit time. This is the expected revenue model of the system or its utility rate after it becomes operational. The system has one failure mode, that it is either functioning or failed; there are no partial failures, the system is not maintainable, and it is characterized by a failure rate $\lambda(t)$ that changes over time. We discretize the time after the system is operational into small ΔT bins over which $u(t)$ and $\lambda(t)$ vary little and can be considered constant:

$$u_n = u(n\Delta T) \approx u[(n+1)\Delta T]$$
$$\lambda_j = \lambda(j\Delta T) \approx \lambda[(j+1)\Delta T] \quad (16)$$

To simplify the indexing, we consider that the revenues the system can generate between $(n-1)\Delta T$ and $n\Delta T$ are equal $u_n \Delta T$ dollars.

Assume that the system is still operational at time $(n-1)\Delta T$. During the following ΔT, it can either remain operational and generate $u_n \Delta T$ dollars, or fail and generate \$0. The probability that the system will fail between $(n-1)\Delta T$ and $n\Delta T$, knowing that it has been operational until $(n-1)\Delta T$, is the conditional probability introduced in Eq. (10) and is related to the failure rate in Eq. (11):

$$Pr[(n-1)\Delta T < T_f \leq n\Delta T | T_f > (n-1)\Delta T] \approx \lambda_n \Delta T \quad (17)$$

Equation (17) represents the probability that the system will fail between $(n-1)\Delta T$ and $n\Delta T$ knowing that it has been operational until $(n-1)\Delta T$. Conversely, the probability that the system will remain operational during this time period knowing that it has not failed before $(n-1)\Delta T$ is

$$Pr(T_f > n\Delta T | T_f > (n-1)\Delta T) \approx 1 - \lambda_n \Delta T \quad (18)$$

Figure 6 is a tree structure that represents the possible outcomes of revenues generated during each small time interval ΔT, along with the probabilities that the system will transition to each state.

The expected revenues generated between $(n-1)\Delta T$ and $n\Delta T$ are equal to the sum of the probabilities times the revenues generated for each outcome, \$0 and $u_n \Delta T$ dollars. They are calculated as

$$\hat{u}_n = (1 - \lambda_n \Delta T) \times u_n \Delta T + (\lambda_n \Delta T) \times 0 = (1 - \lambda_n \Delta T) \times u_n \Delta T \quad (19)$$

The probability that the system remains operational until $(n-1)\Delta T$ is simply the reliability of the system at this point in time R_{n-1}.

We can now calculate the expected present value of a system with the characteristics discussed in the opening paragraph of this section (single mode failure, no maintenance, revenues per unit time $u(t)$, failure rate $\lambda(t)$, and a time bin ΔT small enough to consider $u(t)$ and $\lambda(t)$ constant). When a discount rate $r_{\Delta T}$ is assumed that is adjusted for the time interval ΔT, the expected present value of the system for the period that extends up to $n\Delta T$ is equal to

$$E[PV(n\Delta T)] = R_0[\hat{u}_1/(1 + r_{\Delta T})] + R_1\left[\hat{u}_2\big/(1 + r_{\Delta T})^2\right]$$
$$+ \cdots + R_{n-1}\left[\hat{u}_n\big/(1 + r_{\Delta T})^n\right] \quad (20)$$

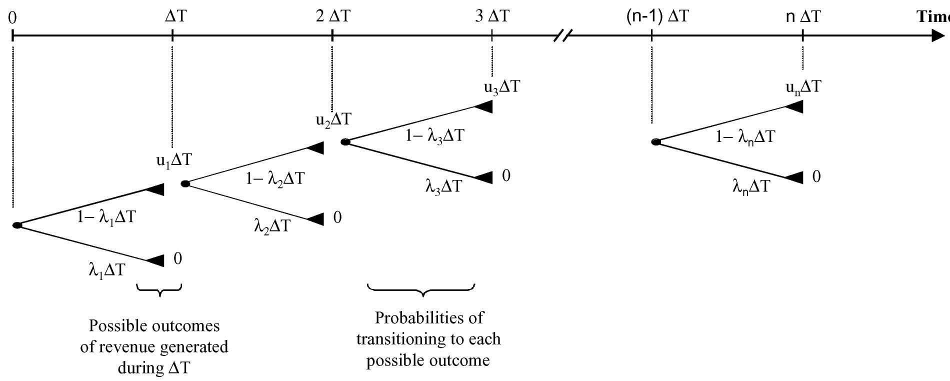

Fig. 6 Possible outcomes of revenues generated during sequence of time intervals ΔT for single mode failure system, along with probabilities of transitioning to each outcome.

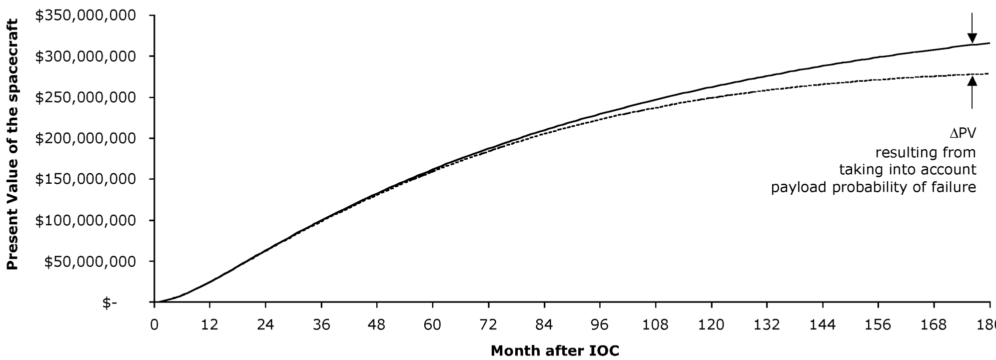

Fig. 7 Present value of communications spacecraft under nominal forecast with 4% per year decrease in *Tx* lease price: ——, expected present value payload reliability accounted for and - - - -, expected present value payload reliability not accounted for.

Replacing the expected revenues $\hat{u}_i$ by their expression given in Eq. (19), we finally get

$$E[PV(n\Delta T)] = \sum_{i=1}^{n} R_{i-1} \frac{(1-\lambda_i \Delta T) \times u_i \Delta T}{(1+r_{\Delta T})^i} \tag{21}$$

C. Communications Satellite Example

We now apply the earlier result [Eq. (21)] of the impact of reliability on a system revenue generation capability and it present value to the case of a communications satellite, using the revenue model developed in Eq. (6). To proceed, a reliability model or, alternatively, a failure rate model (Fig. 5) of the spacecraft and its payload is required. We begin with a general discussion of issues of reliability in spacecraft design, then make a few simplifying assumptions to proceed with our calculations and illustrate how the spacecraft present value differs when reliability is taken into account. We close this section with a discussion of the limitations of the analysis.

1. *Spacecraft Reliability*

In many terrestrial engineered systems, a failure can be tolerated as long as it does not jeopardize the survival of the system or safety of humans. General maintenance procedures preclude designs with complete built-in reliability. Unfortunately, this luxury cannot be afforded in space systems in which on-orbit maintenance is nearly impossible; therefore, reliability is crucial to system survival.[7] For bandwidth providers in the satellite industry, reliability of the communication payload translates into availability, which, in turn, translates into revenue generation.[8] Payload reliability is part of overall system reliability as

$$R_{\text{spacecraft}} = R_{\text{payload}} \times R_{\text{bus}} \tag{22}$$

The spacecraft bus includes all of the subsystems that support the communication payload and provide the so-called housekeeping functions such as structural support, power generation and regulation, thermal management, data handling, and position and orientation determination and control. The reliability of bus subsystems is an important consideration; therefore, commercial satellite manufacturers generally offer platforms (buses) that include full redundancy.

2. *Assumptions*

In the following calculations, we consider only reliability of the satellite communication payload, which is the main revenue generating part of the satellite. With $R_{\text{spacecraft}} < R_{\text{payload}}$, the results obtained are conservative estimates of the negative impact of reliability on revenue generation and the spacecraft present value; in other words, they constitute a lower bound, instead of exact results, of this impact, as Eqs. (21) and (22) indicate. In addition, we consider that the payload amplifiers are independent, that they are either in a failed or operational mode, and that their infant mortality period lasts one year and starts with a value that is three times higher than the constant rate. It decreases linearly to the constant level after one year, then wears out linearly: Only random failures in the spacecraft payload are considered; systemic and common-mode failures are beyond the scope and purpose of this work

$$\lambda(t) = \begin{cases} \lambda_0(3-2t) & \text{for} \quad t < 1 \text{ year} \\ \lambda_0 & \text{for} \quad 1 < t < t_{\text{wear-out}} \\ \lambda_0 + \alpha(t - t_{\text{wear-out}}) & \text{for} \quad t \geq t_{\text{wear-out}} \end{cases} \tag{23}$$

3. *Results*

We first consider no redundancy in the payload and that the high-power amplifiers (HPAs) are traveling wave tube amplifiers (TWTAs). They are characterized by an initial failure rate of 2000 fit that drops within a year to the constant failure rate λ_0 of 660 fit or 660 failures per billion amplifier-operating hours.[9] The wear-out period of the TWTA is assumed to start after the end of the sixth year of operation with a linear increase in the failure rate α of 50 fit per month. This last number (α) is used for illustrative purposes only and bears limited consequences on the results, as will be shown in the sensitivity analysis section. (It is, unfortunately, not available, nor discussed in published handbooks or tables.)

Figure 7 shows the spacecraft present value in the two cases when the payload reliability is accounted for and when it is not. We first

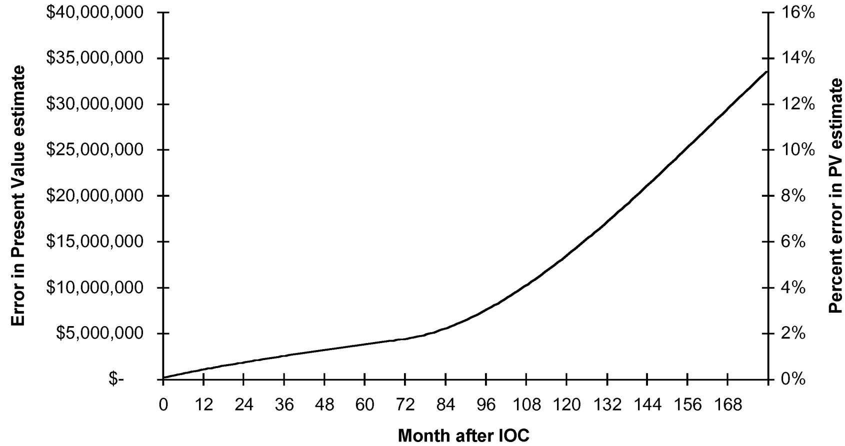

Fig. 8 Error in spacecraft present value estimate when payload reliability is not accounted for.

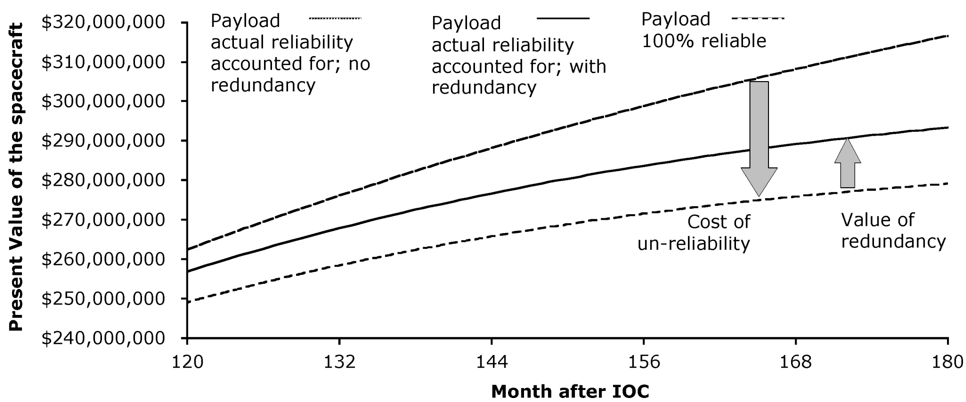

Fig. 9 Present value of communications spacecraft under nominal forecast when 1) payload is considered 100% reliable, 2) payload reliability is accounted for, and 3) reliability and redundancy (50-out-of-70) are accounted for.

note that, under the nominal scenario (load factor $L_0 = 70\%$ and fill rate time constant $\tau = 8$ months), a communications satellite with 50 transponders on-board is worth approximately \$300 million when designed and operated for 15 years. The spacecraft is generating approximately \$3 million per month (Fig. 4), and a 10% discount rate is used for the present value calculation. However, when the payload reliability is accounted for, as calculated in Eq. (21), the satellite expected present value lags behind the preceding calculation as shown in Fig. 7. For a spacecraft designed to operate for 15 years, the difference or error in estimating the spacecraft present value is about \$35 million, or 14% of the estimate that does not account for reliability. Figure 8 shows this estimation error as a function of the intended spacecraft operational lifetime. A general statement can be made at this point: The present value calculation of a spacecraft or any revenue-generating system that does not take into account system's reliability overestimates the system's present value.

Another way of interpreting the results in Fig. 7 is the following: A present value calculation that does not factor in system's reliability, in fact, implicitly assumes that the system remains 100% reliable throughout its intended operational lifetime. The difference between such a calculation and one that does account for reliability can be interpreted as a present value penalty for lack of 100% reliability. For simplification, we call this difference the cost of unreliability and illustrate it in Fig. 8.

4. *Value of Redundancy*

The results discussed assumed no redundancy in the satellite payload. However, in the design of communication satellite payloads, mandatory high-reliability requirements tend to lead designers toward conservative, highly redundant, expensive designs. Same-design redundancy in payload architecture is added by incorporating exact copies of payload components to increase fault tolerance. The cost of same-design redundancy is significantly reduced when M-out-of-N replacement is implemented, in which the spare units $(N–M)$ can replace any one of the active M units. This strategy is commonly employed in the design of the repeaters HPAs, be they TWTAs or solid-state power amplifiers (SSPAs).

In this section, we implement a reliability model that calculates the reliability of a payload repeater with M-out-of-N transponder redundancy level. Here, a repeater means a number of transponders connected by a switch matrix with M operating transponders and $(N–M)$ spare transponders that can replace any failed transponder within the specific repeater under consideration. We consider a communication satellite payload with five repeaters that include a total of up to 50 operating transponders (M) out of 70 available transponders (N). Each of the five repeaters includes up to 10 operating transponders and 4 redundant transponders. Repeater reliability R_{repeater} can be computed from individual transponder reliabilities R_{Tx} for M active transponders out of N available ones as

$$R_{\text{repeater}} = \sum_{K=M}^{N} \binom{N}{K} R_{Tx}^{K} (1 - R_{Tx})^{N-K}$$

$$\text{where} \quad \binom{N}{K} = \frac{N!}{K!(N-K)!} \tag{24}$$

The results are shown in Fig. 9. Figure 9 is focused on year 10 [120 months after international operational capability (IOC)] to year 15 of operations to offer a better read of the differences between the three present value calculations. The first calculation (upper curve in Fig. 9) does not factor in reliability in the present value calculation and, as discussed earlier, is equivalent to considering the system to be 100% reliable throughout its lifetime. Such a calculation, therefore, overestimates the present value of the system as shown in Fig. 7, and Eq. (21) proves this. The second present value calculation (lower curve in Fig. 9) takes into account system's reliability, but does not factor in payload redundancy. The difference between these two calculations was interpreted as a present value penalty for the lack of 100% system reliability, is termed the cost of unreliability, and is illustrated in Fig. 9. The third present value calculation factors in both reliability and redundancy (middle curve in Fig. 9), and we see in Fig. 9 that the curve lies between the two preceding calculations. The present value in this third case is worse than that of the 100% reliable system, but better than that of the no-redundancy system. The result is intuitive and is shown here analytically.

Redundancy provided an increment of present value of around \$10 million compared to the case when no redundancy was implemented. We call this increment the value of redundancy. It is illustrated on Fig. 9 with the upward-pointing arrow.

IV. Spacecraft Value Levers: A Satellite Operator's Perspective

The preceding sections have identified a series of parameters that impact a spacecraft present value. In this section, we describe these parameters as value levers of the spacecraft, impacting the present value positively or negatively. We perform a sensitivity analysis by perturbing these parameters, and explore their impact on the spacecraft present value. This analysis provides an indication to satellite operators on what value levers to pull to maintain or increase the spacecraft value most effectively.

The analyses so far have identified 12 parameters that impact a communications satellite present value. These parameters are summarized in Table 3.

Results of the sensitivity analysis are shown in Fig. 10. Note before we proceed the difference between these results and those illustrated in Fig. 8 and discussed earlier: A sharp observer might have noticed in Fig. 10 that the changes in the reliability parameters of the payload (failure rate, time to wear out, etc.) bear little impact on the spacecraft present value and, thus, conclude that the impact of reliability on a system's present value is of limited importance. Such a conclusion is incorrect: The preceding calculations have shown that not considering the impact of reliability in the case of a communications satellite overestimates the spacecraft present value by over 14%, or \$35 million, for a spacecraft designed to operate for 15 years. This is a significant valuation error. On the other hand, the sensitivity analysis that follows accounts for system's reliability, and, within this more accurate context of valuation [Eq. (21)], the parameters are changed and their impact on system's present value is explored.

We first notice in Fig. 10 that the biggest drivers of the satellite present value are the average lease price of a transponder, the spacecraft load factor, and the total number of transponders in the payload. The impact of each of these parameters on the present value is identical, as can be seen from Eq. (6). From an operator's perspective, preventing the transponder lease price from sliding downward is a first-order reaction for maintaining or maximizing a spacecraft present value. This attitude, however, has to be carefully balanced by considering the lease price elasticity in the market that the spacecraft is serving; in other words, the satellite operator has to consider carefully whether lowering the transponder lease price will allow the operator to capture additional customers, thus increasing the spacecraft load factor and offseting the value lost from the price decrease by a higher utilization of the satellite's payload. Price elasticity is function of the local demand for satellite bandwidth and the competitive intensity over that market (bandwidth demand profile and the operator's market power). Furthermore, in a highly competitive market, the operator should also consider, before pulling on the lease price lever, whether such action will trigger a price war with other operators and, as a consequence, result in a dramatic decrease in satellite present value.

Table 3 Parameters impacting communications satellite present value

Parameter	Description	Nominal value considered
	Market-driven parameters	
L_0	Steady-state load factor	70%
τ	Fill rate time constant	8 months
$\langle P_{Tx} \rangle$	Average Tx lease price	\$1.51 million per year
$\mathrm{d}\langle P_{Tx} \rangle/\mathrm{d}t$	Tx lease price decrease	4.3% per year
	Payload size and reliability parameters	
λ_0	Tx constant failure rate during useful life	660 fit
$t_{\text{wear-out}}$	Beginning of Tx wear-out period	7 years
α	Slope of linear increase in failure rate during wear-out period	50 fit per month
M-out-of-N	Payload level of redundancy	50-out-of-70
Tx_{total}	Total number of Tx onboard spacecraft	50
$T_{\text{infant\_mortality}}$	End of Tx infant mortality period	1 year
β	Slope of linear decrease in failure rate during infant mortality period	110 fit per month
	Financial/market-driven parameter	
r	Discount rate	10%

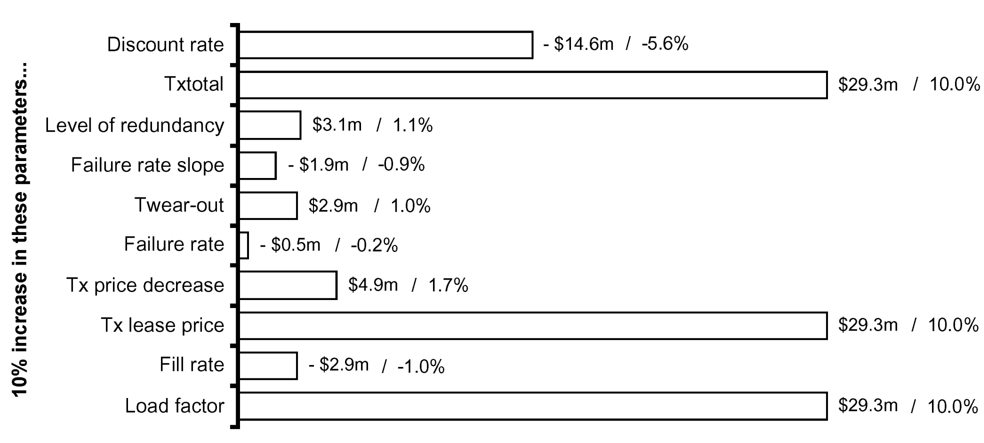

Fig. 10 Sensitivity analysis of spacecraft present value designed to operate for 15 years to changes in nominal values of parameters from Table 3.

Interestingly, we find that the payload reliability characteristics, the transponders failure rate, their time to wear out, and even the level of redundancy bear little consequence on the satellite present value. A 10% change in any of these characteristics results in a 0.2–1.1% change in the present value of a satellite designed to operate for 15 years. Furthermore, a 10% change in the infant mortality parameters (duration and slope) resulted in less than a 0.1% change in the satellite present value. Redundancy, as discussed earlier, has been widely adopted by satellite operators to improve the reliability of their payload. The framework presented in this paper offers a way to quantify the value that redundancy provides for a satellite. For example, when we considered a payload with 50-out-of-70 transponders, the incremental present value that this redundancy provided was around \$10 million for a satellite designed to operate for 15 years. This incremental present value, of course, comes at cost (the additional 20 redundant transponders and their impact on the rest of the spacecraft subsystems). A quick back-of-the-envelope calculation (20 Ku-band TWTA at \$250,000 of each cost of \$5 million) indicates that redundancy may not provide a positive net present value. In addition, the sensitivity analysis confirms that improvements to the payload reliability impact the spacecraft present value in a limited way. An appropriate summary of these findings is the following: Redundancy in communications satellite payload is overrated. In other words, high redundancy levels in communications satellite payloads provide limited incremental value to the spacecraft.

Such a statement, we recognize, goes against conventional wisdom in the aerospace community and may not be kindly looked on by the practitioners. Whereas we do recognize the criticality of redundancy in housekeeping functions onboard a spacecraft, for example, guidance, navigation and control, and electrical power subsystem, the foregoing calculations suggest that high levels of redundancy in a communications satellite payload, given the current state of technology of TWTA and SSPA, is of limited consequence on the spacecraft present value. Redundancy is, therefore, the one value lever that the satellite operator need not pull or invest in. The framework discussed in this paperwork offers a way to transcend qualitative arguments for payload redundancy by quantifying the value that the redundancy provides over the lifetime of a spacecraft. A word of caution, however, is in order: Before sacrificing payload redundancy for present value, careful considerations must be given to end-customers preferences, for example, whether the loss of a transponder without backup can result in a defection or churn of other end customers to healthier satellites (reputation risk resulting from a transponder failure vs value of peace of mind through transponder redundancy).

The last big driver of a satellite present value is the investment's discount rate. A 10% discount rate was used throughout the foregoing calculations. This value is a few points above the risk-free discount rate. Figure 10 shows that a 10% increase in the discount rate results in a −5.6% change in the spacecraft present value. Indeed, a dollar generated, for example, in 10 years, is worth less in present value when discounted at 11% than when discounted at 10%. The discount rate increases with an investment riskiness. Satellite operators have limited control over this lever, but they, of course, know the hurdle rate the investment must clear to be viable (the company's weighted average cost of capital). A discussion of parameters impacting an investment discount rate is beyond the scope of this paper. The interested reader is referred to Ref. 10 for a thorough discussion of the topic.

V. Conclusions

The central finding in this work is that present value calculations of any technical revenue generating system that do not account for system's reliability overestimate the system's present value and, thus, can lead to flawed investment decisions. A framework was developed in this paper that analytically links an engineering concept, a system's reliability, with both managerial and financial concepts, the system's revenue generation capability, and its present value. A communications satellite was used as an example to illustrate the use and insights that can be generated from this framework. For instance, after developing a revenue model for a communications satellite, we quantified the present value penalty for the lack of 100% payload reliability. We termed this penalty the cost of unreliability. Next, we quantified the satellite incremental present value provided by payload redundancy, and termed this increment the value of redundancy. Finally, when performing a sensitivity analysis on the various drivers of the satellite present value, we found, against conventional wisdom, that redundancy in a communications satellite payload is overrated, that is, that increasing payload redundancy provides limited incremental value to the spacecraft. Payload redundancy is, therefore, a value lever of limited impact on the spacecraft present value. Satellite operators need not pull this lever or heavily invest in it in the hope of maximizing their on-orbit asset's worth.

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