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To Reduce or to Extend a Spacecraft Design Lifetime?

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The engineering and economic issues at stake for reducing or extending a complex system's design lifetime are investigated using a spacecraft as an example. These issues are examined from an operator perspective, a manufacturer's perspective, as well as from the perspective of society at large. The question of whether there is an optimal design lifetime for complex engineering systems in general, and spacecraft in particular, and what it takes to answer this question is addressed. Preliminary results indicate that optimal design lifetimes do exist that maximize a system's value metric. Therefore, even if it is technically feasible to field a system or launch spacecraft with a longer lifetime, it is not necessarily in the best interest of an operator, and definitely not in the interest of the manufacturer, to do so. Preliminary results also show that the design lifetime is, in the case of a spacecraft, a key requirement in sizing various subsystems and, consequently, has a significant impact on the overall cost of the spacecraft. Additionally, at the level of the entire space industry value chain, the spacecraft design lifetime is a powerful lever that can significantly impact the whole space industry's performance. Overall, it is shown that the selection of a spacecraft design lifetime begs careful consideration and requires much more attention than it has received so far in the literature because its impact will ripple throughout an entire industry value chain.

Nomenclature

$C(T_{\text{life}})$	=	system cost profile as a function of its design lifetime
$\text{Cost}_{/\text{ops\_day}}$	=	system's cost per operational day
$d\boldsymbol{S}$	=	elemental surface area vector
L_d	=	solar array life degradation
m	=	median
P_{BOL}	=	power at beginning of life
P_{EOL}	=	power at end of life
r	=	discount rate
S	=	closed surface bounding volume V
T_{life}	=	system's design lifetime
$T_{\text{life-max}}$	=	maximum technically achievable design lifetime
$T_{\text{life-min}}$	=	minimum design lifetime for a system to be profitable
T^*_{life}	=	optimal design lifetime
T_{obs}	=	time to obsolescence
$t_{\text{break-even}}$	=	time to break even
$\boldsymbol{U}$	=	flow velocity vector
$u(t)$	=	utility rate of a system, for example, revenues per day for a commercial system
V	=	control volume
$V(T_{\text{life}})$	=	expected present value of a system as a function of its design lifetime
$\theta(t)$	=	cost per day for operating the system
ρ	=	fluid density
σ	=	standard deviation
τ	=	waiting time or shift parameter

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I. Introduction

THERE is a popular belief that manufacturers of durable goods often deliberately reduce the time period for which their products remain operational to increase their sales and profits. For instance, it seems that the electric lamp industry in the United States in the 1960s "has served to limit, and frequently reduce, lamp life in order to increase sales" when customers' interests were generally thought to be better served by bulbs of much longer life.[1] This hypothetical practice has sparked environmental concerns among ecologists and policy makers and created interest in the contribution that extended product design lifetime can make toward reducing the waste management and other environmental problems.[2] Several industries, however, strongly denied having a concealed policy of either deliberately limiting product operational life, or of accelerated product obsolescence, that is, introducing upgrades or new functionalities in a product to promote customer dissatisfaction with existing products and promote sales of new products.[3]

The example just discussed is used for two purposes. First, it introduces the three main stakeholders that should be taken into account when analyzing issues of product durability and system design lifetime, namely, the customer, the manufacturer, and society at large. Second, the example portrays tension between the stakeholders as each is affected differently by an extended or reduced product lifetime and shows that the interests of the one are not necessarily aligned with the interests of the other. Therefore, we recognize that when exploring the issues at stake in reducing or extending a product durability, it is necessary to first specify from which stakeholder perspective the analysis is carried out because the interests and tradeoffs can be substantially different.

Academic interest in product durability peaked in the 1970s and early 1980s, then temporarily faded out only to resurface in the 1990s and grapple with issues of planned obsolescence of computer hardware and software. However, beyond product durability, questions emerge pertaining to engineering system design lifetime. Product durability and system design lifetime are similar in that they both characterize an artifact's relationship with time. The difference, however, is one of complexity and scale. In the following paragraphs, we define system design lifetime as a requirement that specifies to the manufacturer the duration for which a system should remain operational. This requirement can be specified either by the customer or by the designer, or imposed by the market or by society. Design lifetime differs from product durability in that it is mainly used to characterize the duration of intended operation for complex engineering systems, as opposed to products of limited complexity and functionalities.

System design lifetime, unlike product durability, has received almost no attention in the technical literature, either from academics or from industry professionals. Yet the engineering and economic issues associated with system design lifetime do offer a rich field of investigation for academics and industry professionals. In the following sections, we show that the design lifetime is a key requirement in sizing various subsystems, using a spacecraft as an example, and that its specification begs careful consideration and requires much more attention than it has received so far in the literature[4] because its impact is substantial and can ripple throughout an entire industry value chain.

This paper is organized as follows. In Sec. II, a series of qualitative implications for reducing or extending a system's design lifetime are synthesized and discussed, as seen from the perspective of three stakeholders, namely, the customer, the manufacturer, and society at large. In Sec. III, whether there is an optimal design lifetime for a complex engineering system is investigated as seen from a customer's perspective: This section first advocates a mindset change necessary to address the question of design lifetime optimality and discusses the notion of a system as a value delivery artifact. In Sec. III, a quantitative analyses and illustrative results are then provided using a communications satellite as an example. (The results show that, under certain assumptions, satellites do have optimal design lifetimes that maximize a value metric.) Sensitivity analysis is performed and implications of these results are further discussed. In Sec. IV, we switch from a customer's perspective to a manufacturer's perspective as is specific to satellite manufacturers. To illustrate the possible implications of reducing vs extending a satellite design lifetime, in Sec. IV, the provocative question of whether satellite manufacturers are driving themselves out of business by designing for increasingly longer lifetime is asked. In effect, in Sec. IV we investigate the impact of changing a satellite design lifetime on the forecast demand for satellite communications. Finally, in Sec. V, we conclude with the summary and implications of this work.

II. Qualitative Arguments for Reducing or Extending Product Durability or System Design Lifetime

In this section, we discuss the qualitative implications associated with reducing vs extending a product durability or a system design lifetime, as seen from the perspective of the three stakeholders already introduced, namely, the customer, the manufacturer, and society at large. Table 1 synthesizes our findings. We have tagged each implication with a numeral followed by an A or a D for what appeared to us more as an advantage or a disadvantage. Note that in some cases the customer of a system is not the end user. For example, satellite operators are customers of satellite manufacturers; however, the end users are television broadcasters, communications carriers, service providers, or others. More generally, there are numerous stakeholders for complex engineering systems: In our satellite industry example, stakeholders other than the satellite manufacturers and operators include end users, launch services, equipment manufacturers, insurance companies, and regulatory agencies. All stakeholders are affected to some extent, and often differently, by the system's design lifetime. We acknowledge, therefore, that our discussion and Table 1 are not exhaustive but confined to the three stakeholders mentioned.

Table 1 Implications scorecard for reducing or extending a system design lifetime

To reduce (reduced) design lifetime			To extend (extended) design lifetime		
Customer's perspective	Manufacturer's perspective	Society's perspective	Customer's perspective	Manufacturer's perspective	Society's perspective
1A) Family of products more likely to be improved through more frequent iterations of fielding and feedback to the manufacturer, than products with longer lifetimes	1A) Ability to improve subsequent products through more frequent iterations of fielding and customer feedback	1A) Shorter design lifetime can stimulate faster innovation and technological progress	1A) Smaller volume of purchasing	1A) Service contracts have the potential to generate higher profits that the mere sale of the product or system	1A) Products with longer design lifetimes result in less waste during a given time period than those with shorter lifetimes
	2A) Potential for higher sales volume	2A) Potential for maintaining and boosting industry employment level through higher sales volume	2A) Potentially smaller cost per operational day	2A) Increased design lifetime acts as a magnifier of reliability as a competitive advantage; product reliability is less critical for short lifetime than for products with longer lifetime	2A) Longer design lifetime can stimulate the creation of a secondary market for the products
	3A) Heightened obligation for employees to remain technically up to date and attentive to the voice of the customer	3A) Old products are easier to replace than repair, hence the likelihood of more state-of-the-art products in use than with products with longer lifetimes			
1D) Need to purchase more products for a given duration	1D) Fewer opportunities for revenues from services	1D) Adverse environmental effect as a result of more product disposal during a given time period	1D) Increased risk the product will be technically or commercially obsolete before the end of its lifetime, hence loss of revenues	1D) Extended warranty needed, which may result in higher levels of unpaid services	1D) Increased risk of technological slowdown, potential increase in an industry's unemployment

A. Implications of Reducing (or a Reduced) Design Lifetime

In this section, we discuss the qualitative implications for reducing product durability or system design lifetime.

From a customer's perspective, a product or a family of products with a shortened lifetime is more likely to be improved on, during a given time period, through more frequent iterations of fielding and feedback to the manufacturer, than products with longer lifetimes. One disadvantage, however, the customer could perceive if the duration of the needed service exceeds the system design lifetime is the need to purchase increasingly more products as their lifetimes decreases.

From a manufacturer's perspective, these two points translate into advantages: First, manufacturers of products or family of products with shortened lifetime have an increased ability to improve their products through more frequent iterations of fielding and customer feedback. Second, shorter lifetime can stimulate sales because customers need to buy more volume to sustain the same level of service during a given time period. For example, in the sports industry, "Professional teams constantly update their merchandise to keep the public spending uniformly."[5] Another implication of shortened lifetime is a heightened obligation for the employees to remain technically up to date and attentive to the voice of the customer to fend off competitors. This we believe is the case because customers of systems with short design lifetime are not locked in for as long of a duration as customers who acquire longer lived products; these customers can, therefore, more frequently recommit resources to acquiring new products or systems from the competition, if the incumbent is not constantly offering best value products. One disadvantage for manufacturers of reducing system design lifetime is the limited opportunities they have to generate revenues from service contracts. This can represent a substantial opportunity loss. However, this opportunity loss should be analytically compared to the increased volume of sale and revenues associated with it before manufacturers decide whether they are better off reducing or extending the product durability or system design lifetime.

From a society's point of view, short design lifetime present several advantages. First, shorter design lifetime can stimulate a faster pace for innovation and technological progress. Planned obsolescence or short-lived products but fast innovation may be preferred, from a society's perspective, to long-lasting products and a slow pace for innovation. Second, if the assumption we just discussed is true, namely, that products with shorter lifetime can stimulate sales because customers need to buy more volume to sustain the same level of service during a given time period, then this increased sales volume has the potential to maintain or boost industry employment. Third, old products are likely easier to replace than to repair than products with longer lifetimes. More state-of-the-art products, therefore, are likely to be found more in use at any given time than if these products were designed for longer lifetime. One adverse environmental effect, however, associated with shortened lifetimes results from an increased number of products to dispose of during a given time period.

B. Implications of Extending (or an Extended) Design Lifetime

In this section, we discuss the qualitative implications for extending product durability or system design lifetime. The reader will notice that some of the stakeholders' advantages in reducing a system design lifetime transform into disadvantages when longer design lifetime are considered and vice versa.

From a customer's perspective, purchasing products or systems with long lifetime offers mainly two advantages. First, customers have to purchase fewer products or systems for the duration of their service needs because the design lifetime increases. Second, it is more likely that the product or system's cost per operational day decreases as the system's design lifetime increases. This point will be discussed in more detail in the following analytical sections. One disadvantage a customer will encounter with longer lived systems is an increased risk that these systems will be technically and commercially obsolete before the end of their lifetimes, hence, an increased risk of loss of revenue.

From a manufacturer's perspective, there are two main implications associated with an increased system design lifetime. First, systems with long design lifetime offer manufacturers a heightened ability to generate additional revenues, and higher profits, from service contracts than from the mere sale of the system. (Note that for satellites, manufacturers normally do not have service contracts but usually provide anomaly support through the contracted life on-orbit at no cost to the operator.) There is limited potential for additional revenues from services with system of short design lifetime. The second implication, which is neither an advantage nor a disadvantage, merely an observation follows. Increased design lifetime acts as a magnifier of system's reliability as a competitive advantage. That is, the reliability of a system is increasingly more valuable for customers as the system design lifetime increases. Therefore, manufacturers with core competencies to produce highly reliable systems have some incentives to increase their systems design lifetime to augment the quality gap with manufacturers of less reliable systems and, therefore, augment their market share at the detriment of the competition. One risk manufacturers have to deal with when extending their system design lifetime is the need to offer equally extended warranty, which may result in higher levels of unpaid services. This risk is heightened for manufacturers of lesser reliable systems. In other words, manufacturers who do not have a track record in designing distinctively reliable systems should carefully consider before engaging in design lifetime extension behavior to differentiate their systems from the competition's. This risk should be weighted against, or can be mitigated by, the service contract advantage discussed earlier.

From a society's point of view, one clear environmental advantage of systems with long design lifetime is that the use of such artifacts result in less waste to be disposed of during a given time period than shorter lived products or systems. Another implication is that long design lifetime can stimulate the creation of a secondary market for products, hence, an increased economic activity. One disadvantage, however, that can result from fielding systems with increasingly longer lifetime is that, whereas short design lifetime can stimulate a faster pace for innovation, long design lifetime can increase the risk of technological slowdown and adversely impact an industry employment level.

In the preceding sections, we synthesized and discussed the different qualitative implications associated with reducing vs extending a product durability or a system design lifetime, as seen from the perspective of three stakeholders, namely, the customer, the manufacturer, and society. The purpose of this qualitative discussion was to illustrate the complexity of the choice in reducing or extending a system's design lifetime, not to take a position for reducing or extending this requirement, and to lay the ground for the quantitative discussion to follow.

C. Example: To Reduce or To Extend a Spacecraft Design Lifetime? An Operator's Perspective

Over the past two decades, telecommunications satellites have seen their design lifetime on average increase from 7 to 15 years. Increasing the space segment lifetime was driven by both the desire of satellite operators to maximize their return on investment and by the determination of manufacturers to offer spacecraft with longer lifetime as a competitive advantage for their spacecraft in the hope of increasing their market share. (It is legitimate, however, to ask whether this competitive behavior is not in effect hurting satellite manufacturers by limiting the market need for additional spacecraft and shrinking the satellite replacement market.)

Extending satellite design lifetime, however, has several side effects. On the one hand, it leads to larger and heavier satellites as a result of several factors, such as additional propellant for orbit and station keeping or increased power generation and storage capability. This in turn increases the satellite's development and production cost. On the other hand, as the design lifetime increases, the risk that the satellite becomes obsolete, technically and commercially, before the end of its lifetime increases. This tradeoff is shown in Fig. 1.

The preceding discussion indicates that, in specifying spacecraft design lifetime requirement, operators have to assess the risk of loss

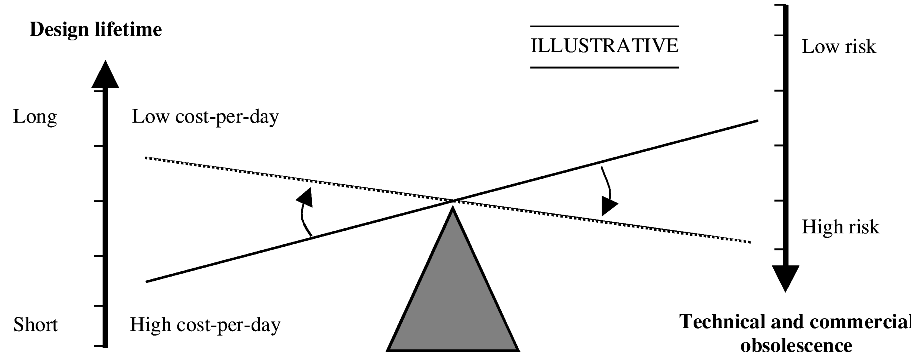

Fig. 1 Design lifetime tradeoffs.

of value due to both obsolescence of their spacecraft technology base as well as the likelihood of changing or shifting market needs after the satellite has been launched. For example, it is not obvious to be in the best interest of a satellite operator to make the contract life of a spacecraft too long: New or enhanced capabilities, for example, better spatial resolution for an optical instrument, might be developed and become available within a couple of years following the launch; hence, there is a need to launch a new satellite or risk losing market share to a competitor who launches later with newer or more advanced capabilities. How then can we capture the value of a system (or the loss of it) as a function of its design lifetime? The following sections offer some suggestions toward this goal.

III. Is There an Optimal Design Lifetime for Complex Engineering Systems? A Customer's Perspective

Questions regarding the design lifetime of complex engineering systems fall into three categories:

1) What limits the design lifetime? How far can designers push the system's design lifetime? What is the lifetime boundary, and why can it not be extended?

2) How do the different subsystems scale with the design lifetime requirement, and what is the total system cost profile as a function of this requirement?

3) What does (or should) the customer ask the contractor or manufacturer to provide for a design lifetime and why?

The first question is purely a technical/engineering one and addresses the issue of lifetime boundary. For instance, what prevents engineers from designing a spacecraft for, for example, 100 years? Current satellites are launched with design lifetime of 12–15 years. Solar array degradation due to thermal cycling in and out of eclipses, micrometeoroid strikes, radiation damage, and material outgassing offer serious challenges for engineers to overcome if the current 15-year mark of spacecraft design lifetime is to be extended. Other limitations result from battery technology (number of charge/discharge cycles possible), inertial systems degradation and failure, as well as electronics degradation both in the telemetry, tracking, and control subsystem of a spacecraft as well as its payload due to space radiation.

The second question focuses on the effects of varying the design lifetime requirement on each subsystem. We explored in a previous work[6] how different spacecraft subsystems scale as a function of the design lifetime requirement, then aggregated the results and derived total spacecraft mass and cost profiles as a function of this requirement. We found that the design lifetime is a key requirement in sizing various subsystems and that typically 30–40% mass and cost penalty are incurred when designing a spacecraft for 15 years instead of 3 years, all else being equal. More generally, the answer to this second question in the case of any complex engineering system constitutes a mapping between a system design lifetime and the investment necessary to develop or acquire such a system. The answer to this second question also provides another confirmation of the old adage, from a different angle though, that time is money, that is, more system lifetime requires more money to develop or acquire.

The third question builds on the two preceding ones and is mainly a management decision that should be supported by engineering and market analyses as well as financial evaluation: Given the maximum achievable design lifetime (answer to question 1) and given the impact of the design lifetime on the system cost (answer to question 2), what should the customer ask the contractor to provide for a design lifetime? Is there a value metric that can be maximized through the selection of an optimal design lifetime? What should be taken into account when evaluating this metric? These questions are addressed in the following sections. We first discuss what it takes to answer the design lifetime optimality question.

A. Prerequisite: A Mindset Change

How can we capture the value of a system as a function of its design lifetime? To do so, we first need to augment our understanding of system design and architecture. System architecting is traditionally viewed as a matching between two (vector) quantities, resources and system performance. One traditional design paradigm fixes the amount of available resources and optimizes the system performance given this constraint. The other approach constrains the system performance to a desired level and strives to find a design that will achieve this performance at minimal cost.[7] The first approach operates with, and attempts to maximize, a performance per unit cost metric; the second approach seeks to minimize a cost per function (or performance) metric. To discuss (quantitatively) issues related to the design lifetime, it is imperative that we view in a system the flow of service (or utility) it will provide over a given period of time. Therefore, we need to introduce cost, utility, and value per unit time metrics to guide the selection the design lifetime.

B. Value of a System as a Function of Its Design Lifetime

To specify the design lifetime requirement, a customer needs to be able to express the present value of a system as a function of its design lifetime. We propose the following equation as a means for capturing this value:

$$V(T_{\text{life}}) = \int_0^{T_{\text{life}}} [u(t) - \theta(t)] \times e^{-rt}\,\mathrm{d}t - C(T_{\text{life}}) \tag{1}$$

Equation (1) is conceptually analogous to the continuity equation (or conservation of mass) in fluid dynamics, which in its integral form is

$$\frac{\partial}{\partial t}\int_V \rho\,\mathrm{d}V + \int_S \rho \mathrm{U}\,\mathrm{d}S = 0 \tag{2}$$

The analogy between the two equations is shown in Fig. 2. The control volume becomes a time bin, the system's design lifetime. The flow entering the control volume is analogous to the aggregate utility or revenues generated during the time bin considered, and the flow exiting the volume corresponds to the cost of acquiring a system designed for this time bin, T_{life}, plus the cost to operate it during the same period.

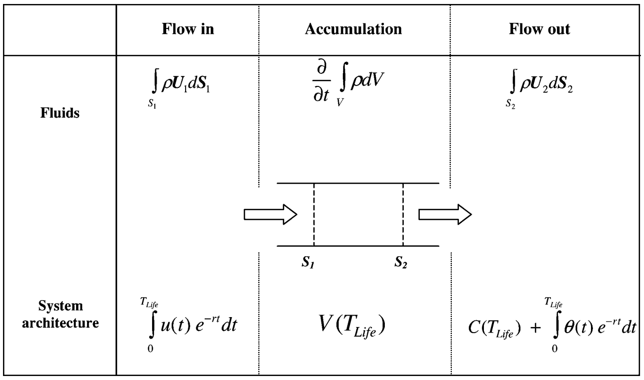

Fig. 2 Analogy between expected present value of a system as a function of its design lifetime equation (1) and the continuity equation in fluid dynamics.

Two time characteristics can be readily derived from Eq. (1): the minimum design lifetime for a system to be profitable and the time of operations for a system to break even given a design lifetime. These are discussed next.

1. Minimum Design Lifetime for a System To Be Profitable

The minimum design lifetime for a system to become profitable can be computed by setting $V(T_{\text{life}})$ to zero:

$$V(T_{\text{life-min}}) = \int_0^{T_{\text{life-min}}} [u(t) - \theta(t)] \times e^{-rt}\, dt - C(T_{\text{life-min}}) = 0$$

$$V(T_{\text{life}}) > 0 \qquad \text{for} \qquad T_{\text{life}} > T_{\text{life-min}} \tag{3}$$

Whereas technical considerations limit the upper bound of system design lifetime, as we already discussed, the lower bound on the design lifetime, as seen from a customer perspective, is dictated by economic considerations and is given by the solution to Eq. (3). Note that the minimum design lifetime for a system to be profitable is not identical to the time to break even. This second time characteristic of a system is discussed next.

2. Time to Break Even Given a Design Lifetime

The time for a system to break even is given by the solution of Eq. (4) in which T_{life} is fixed. In other words, once the system's design lifetime is specified, time is allowed to vary until the discounted revenues cover the cost to design the system for T_{life}, $C(T_{\text{life}})$, in addition to the discounted cost to operate the system until $t_{\text{break-even}}$:

$$V(T_{\text{life}}, t_{\text{break-even}}) = \int_0^{t_{\text{break-even}}} [u(t) - \theta(t)] \times e^{-rt}\, dt - C(T_{\text{life}}) = 0 \tag{4}$$

The comparison between the time to break-even and the minimum design lifetime is as follows: when $T_{\text{life}} < T_{\text{life-min}}$, $t_{\text{break-even}}$ does not exist; when $T_{\text{life}} = T_{\text{life-min}}$, $t_{\text{break-even}} = T_{\text{life-min}}$, and when $T_{\text{life}} > T_{\text{life-min}}$, $t_{\text{break-even}} > T_{\text{life-min}}$.

How can these equations be useful? Let us assume, for instance, that the management of a company about to acquire a large complex system wants to break even in $t_{\text{break-even}}$ years. What is the average revenue per day u_0 that the company should guarantee from the system to do so? The answer is given by

$$\int_0^{t_{\text{break-even}}} u_0 \times e^{-rt}\, dt = C(T_{\text{life}}) + \int_0^{t_{\text{break-even}}} \theta(t) \times e^{-rt}\, dt \tag{5}$$

Therefore,

$$u_0 = r \times \frac{C(T_{\text{life}}) + \int_0^{t_{\text{break-even}}} \theta(t) \times e^{-rt}\, dt}{1 - e^{-rt_{\text{break-even}}}} \tag{6}$$

Assuming that the cost to design the system is larger than the cost to operate it, that is,

$$C(T_{\text{life}}) \gg \int_0^{t_{\text{break-even}}} \theta(t) \times e^{-rt}\, dt$$

and recalling that $e^x = 1 + x + \varepsilon(x^2)$, we get

$$u_0 \approx \lfloor C(T_{\text{life}})/T_{\text{life}} \rfloor \times (T_{\text{life}}/t_{\text{break-even}}) \tag{7}$$

In a previous work,[6] we introduced the concept of cost per operational day for a spacecraft. We defined this metric as the ratio of the spacecraft cost to initial operational capability (IOC) and its design lifetime, expressed in days,

$$\text{Cost}_{/\text{ops\_day}} = \frac{\text{cost to IOC}}{\text{design lifetime (days)}} \tag{8}$$

More generally, we can define an engineering system's cost per operational day as follows:

$$\text{Cost}_{/\text{ops\_day}} = \frac{C(T_{\text{life}})}{T_{\text{life}}(\text{days})} \tag{9}$$

This definition corresponds to amortizing the cost of a system uniformly, excluding the cost to operate it, over its intended design lifetime. When we go back to Eq. (7) and the question that prompted that analysis, namely, what is the average revenue per day u_0 that a company should guarantee from the system to break even in $t_{\text{break-even}}$ years, we found the answer in Eq. (7), the first term of which is the system's cost per operational day. This result can prove useful in feasibility studies or back-of-the-envelope calculations. For instance, assume a company that is acquiring a \$100 million system designed for 10 years wishes to amortize its investment in 2 years. To do so, the company should guarantee average revenues per day at least five times more than the system's cost per operational day:

$$u_0 \approx \left(\frac{100 \times 10^6}{10 \times 365}\right) \times \frac{10}{5} \approx \$55{,}000/\text{day}$$

Conversely, if market analysis indicates that the service provided by this system can at best generate \$30,000/day, considering the market size and the presence of other players in this market, then the time to amortize the investment is

$$t_{\text{break-even}} \approx \left(\frac{100 \times 10^6}{10 \times 365}\right) \times \frac{10}{30{,}000} \approx 9.1 \text{ years}$$

It is likely, given this result, that the senior management of the company will reconsider before acquiring the system with its 10-year design lifetime.

C. Quantitative Analyses Required for Answering the Optimality Design Lifetime Question

We set up to investigate whether an optimal design lifetime exists for complex engineering systems: optimality as seen from the customer's perspective. To answer this question, the discussion first led us to advocate a mindset change about system design and architecture: namely, to view in a system the flow of service it will provide over a given time period. This led us to recognize the need for system-level metrics, such as cost, utility, and value per unit time. Second, optimality presupposes a metric that is minimized or maximized; we, therefore, proposed Eq. (1) as a means for capturing the present value of a system as a function of its design lifetime. We can now mathematically formulate our question regarding the existence or not of an optimal design lifetime for complex engineering systems, as seen from the customer's perspective:

$$V(T_{\text{life}}) = \int_0^{T_{\text{life}}} [u(t) - \theta(t)] \times e^{-rt}\, dt - C(T_{\text{life}})$$

$$\text{Is there a } T^*_{\text{life}} \text{ such that } V(T^*_{\text{life}}) > V(T_{\text{life}}) \text{ for all } T_{\text{life}} \neq T^*_{\text{life}}? \tag{10}$$

To investigate this problem, several analyses and models are required: 1) engineering and cost estimate analyses of the system cost profile $C(T_{\text{life}})$, 2) market analyses and forecast of system expected revenue model $u(t)$, 3) technical analysis and estimate of cost to operate and maintain the system $\theta(t)$, and 4) financial analysis of the investment risk, usually referred to as beta, which in turn is used to derive the appropriate risk-adjusted discount rate for the investment, r.

We performed some of the analyses in the case of commercial spacecraft wherever possible and used proxies or generic models in other cases. We briefly discuss our methodology and findings in the following subsections.

1. Engineering and Cost Estimate Analyses of System Cost Profile $C(T_{\text{life}})$

How does the design lifetime requirement impact the sizing of the different subsystems onboard a spacecraft? Consider the solar arrays, for example. Life degradation is a function of the design lifetime. It occurs for a number of reasons, for example, radiation damage and thermal cycling in and out of eclipse, and is estimated as follows:

$$L_d = (1 - \text{degradation/year})^{T_{\text{life}}} \tag{11}$$

The degradation per year is a function of the spacecraft orbital parameters (position with respect to the Van Allen belts), as well as the solar cycle. It varies typically between 2 and 4% (Ref. 1) The solar array's performance at the end of life (EOL) compared to what it was at beginning of life (BOL) is given by

$$P_{\text{EOL}} = P_{\text{BOL}} \times L_d \tag{12}$$

Given a power requirement at EOL, the power output of the solar arrays at BOL scales inversely with life degradation and the solar arrays have to be overdesigned to accommodate this performance degradation. This overdesign of the solar arrays translates into mass and cost penalty as the design lifetime increases. Batteries, which can constitute up to 15% of the dry mass of a typical communications satellite,[8] are also significantly impacted by the spacecraft design lifetime requirement. The amount of energy available from the batteries, or depth of discharge (DOD), decreases with the number cycles of charging and discharging. To first order, the number of charge/discharge cycles is equal to the number of eclipses a satellite undergoes during its design lifetime. Typically, a satellite in GEO undergoes two periods of 45 days per year with eclipses, hence, 90 cycles of charging and discharging per year. As the design lifetime increases, the number of charging/discharging cycles a battery has to undergo increases. Therefore, its DOD decreases. For example, for a 3-year spacecraft lifetime in GEO, the average DOD for a nickel–cadmium battery is approximately 76%, but it drops to 62% for a spacecraft lifetime of 10 years. Battery capacity scales inversely with the DOD; therefore, as the spacecraft design lifetime increases, batteries have to be overdesigned to compensate the reduction in DOD. This result again in a mass and cost penalty for the spacecraft as its design lifetime increases.

The design lifetime is a key requirement in sizing all of the subsystems onboard a spacecraft, not just the solar arrays and batteries. When we aggregate the direct and indirect impact of the design lifetime on all subsystems, we generate typical spacecraft mass profiles as a function of the design lifetime. Then, using spacecraft cost estimate relationships developed over the years by various organizations, relating subsystem cost to physical or technical parameters, we generate spacecraft cost profiles as functions of the design lifetime, our sought-after $C(T_{\text{life}})$. Typical results of $C(T_{\text{life}})$ and spacecraft cost per operational day are shown in Figs. 3 and 4. We see cost penalties of 30–40% when designing a spacecraft for 15 years instead of 3 years. A more elaborate discussion of these results, along with their limitations, is provided in Ref. 6.

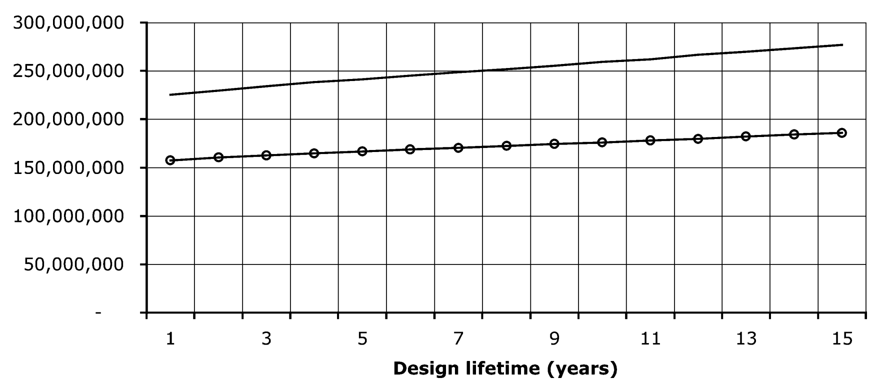

Fig. 3 Spacecraft $C(T_{\text{life}})$ or cost to IOC as function of design lifetime requirement spacecraft in GEO, mission reliability = 95%, GaAs cells, Ni–H2 batteries: ○, 5-kW EOL, 250-kg payload and ——, 10-kW EOL, 400-kg payload.

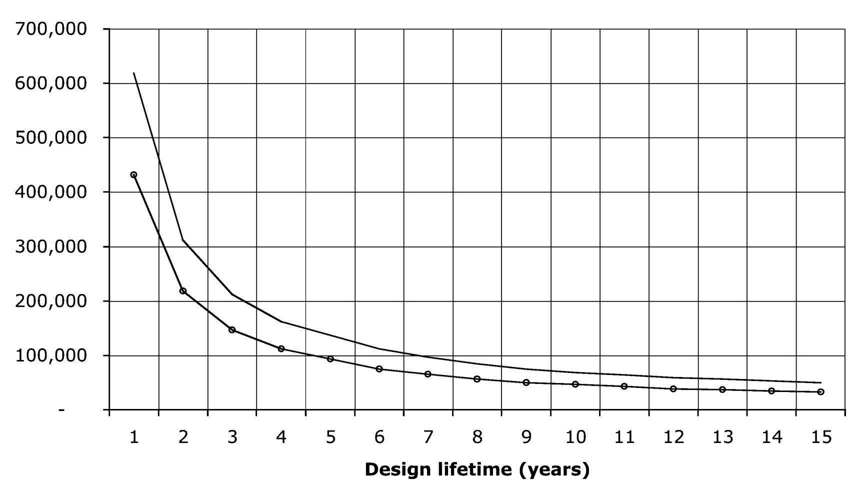

Fig. 4 Spacecraft cost-per-operational day ($/day) as a function of the design lifetime (same parameters as in Fig. 3): ○, 5-kW EOL, 250-kg payload and ——, 10-kW EOL, 400-kg payload.

The spacecraft cost per operational day decreases monotonically. In the absence of other metrics, this behavior of the cost per operational day may justify pushing the boundary of the design lifetime and designing spacecraft for increasingly longer periods. It also suggests that a customer is always better off requesting the contractor to provide the maximum design lifetime technically achievable:

$$T_{\text{Life-best}} = T_{\text{Life-max}} \tag{13}$$

This may be valid in a "cost-centric" environment, but is not necessarily true in a "value-centric" environment, as we will show later.

2. *Market Analyses and Forecast of System Expected Revenue Model $u(t)$*

After the system cost profile $C(T_{\text{life}})$, the second model required to demonstrate the existence or not of an optimal design lifetime consists of market analyses and forecast of the system's expected revenue model $u(t)$. In the case of a noncommercial system, the revenue model can be replaced by an expected utility profile of the system as a function of time. For a communications satellite in GEO, the revenue model should depend on the following:

$$u(t) = u(\text{longitude, number of transponders, service mix,}$$
$$\text{market volatility, technology obsolescence, etc.}) \tag{14}$$

The spacecraft longitude provides both an indication of the market size the operator can tap into as well as the competitive intensity over this market (which in turn drives the service price). Spacecraft prime locations have traditionally been over the Americas, Europe, as well as trans-Atlantic longitudes. The number of transponders as well as the service mix (audio, video, data) are also important parameters that define a communications satellite revenue profile. Finally, the volatility of the market the satellite is intended to serve and the obsolescence of the system's technology base have to be factored in when forecasting a satellite revenue profile as a function of time, $u(t)$.

When we set up to investigate communications satellite revenues, we were surprised to find that, whereas numerous spacecraft cost models exist and are widely available, no (published) spacecraft revenue models exist. 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. We are currently working with industry partners on developing communications satellites revenue models that appropriately capture the dependencies shown in Eq. (14). For this paper, we use two simple spacecraft revenue models (based on simple calculations using satellite operators' income statements) and generic obsolescence models.

Simple case. We consider the revenues per day generated by the satellite to be constant over its design lifetime: no ramp-up/fill rate, market volatility, or obsolescence issues taken into account. The numbers, based on simple calculations using satellite operator's income statement, average transponder lease (\$million/year), average number of transponders per satellite, and utilization rate, typically vary between \$50,000 and \$100,000 per day:

$$u_1(t) = u_0 \tag{15}$$

Technology obsolescence case. In the second case, we consider the impact of the technology obsolescence on the spacecraft revenue model. We assume a model exists that relates component obsolescence to system's obsolescence and that a timescale of obsolescence affects the system's revenues as follows:

$$u(t) = u_0 \times \exp\left\lfloor -(t/T_{\text{obs}})^2 \right\rfloor \tag{16}$$

See Refs. 7 and 9 for a more elaborate discussion of this model's rationale, assumptions, and limitations. Time to obsolescence can be modeled in the simple case as a deterministic variable, or more appropriately as a random variable with a lognormal probability density function[9]:

$$p(\hat{T}_{\text{obs}}) = \frac{1}{\left(\sigma\sqrt{2\pi}\right)(\hat{T}_{\text{obs}} - \tau)} \times \exp\left\lfloor -\left\{\frac{\log[(\hat{T}_{\text{obs}} - \tau)/m]}{\sigma\sqrt{2}}\right\}^2 \right\rfloor \tag{17}$$

Figure 5 shows the lognormal density function as well as the cumulative density function of the time to obsolescence for a typical microprocessor.

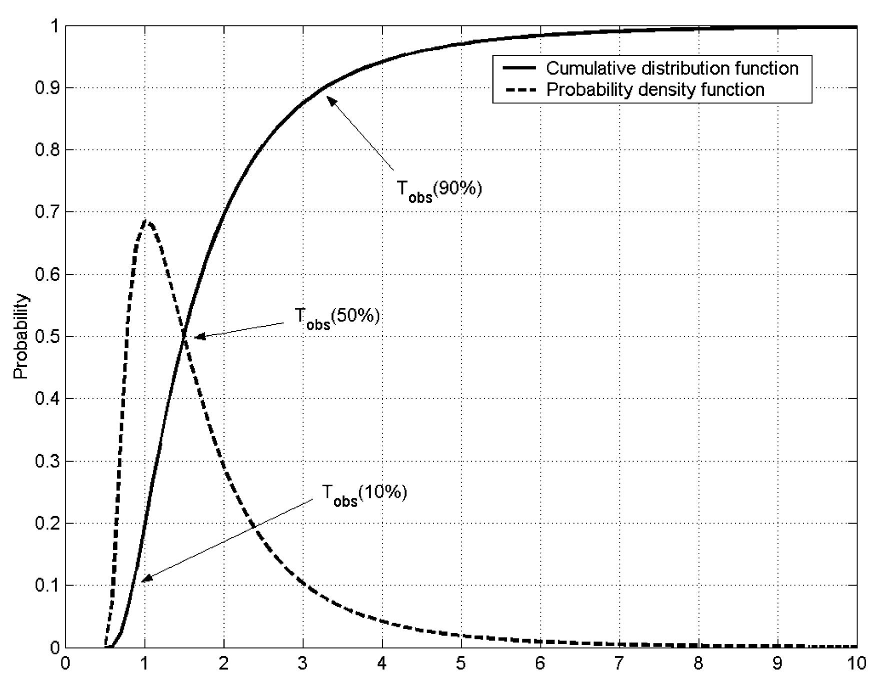

Fig. 5 Cumulative distribution function and probability density function of time to obsolescence for microprocessor: $m = 1.5$ years, $\sigma = 0.8$ years, and $\tau = 0.5$ years.

3. Technical and Financial Analyses: Operations Cost, $\theta(t)$, and Discount Rate r

The last two models or parameters needed to demonstrate the existence or not of an optimal design lifetime are estimates of the cost to operate and maintain the system $\theta(t)$ and the risk-adjusted discount rate that the company may wish to use for its investment in the system, r.

In the case of spacecraft, mission operations are described in detail in Ref. 10. The cost per year to operate a satellite typically varies between 5 and 15% of the spacecraft cost to IOC. In our analysis, we consider the cost of operations $\theta(t)$ to be constant and equal to 10% of $C(T_{\text{life}})$ and perform our sensitivity analysis around this value. This assumption, however, has little effect on our results and bears no consequences on our conceptual findings as we will show subsequently.

We use a discount rate r of 10%. This is a commonly used figure and a few percent points above the risk-free rate of return. We perform a sensitivity analysis around this value.

D. Illustrative Results

Using the models and assumptions discussed earlier, we can now explore the solution to Eq. (10), namely, whether an optimal design lifetime exists for a satellite, as seen from a customer's perspective, that maximizes the expected present value of a system as a function of its design lifetime, $V(T_{\text{life}})$. The results are shown in Figs. 6 and 7.

Several observations can be made:

1) Given our assumptions, an optimal design lifetime exists that maximizes the expected present value of a satellite as a function of its design lifetime $V(T_{\text{life}})$. In other words, even if it is technically feasible to design a spacecraft for an extended lifetime, it is not necessarily in the best interest of the customer to ask the contractor to provide a spacecraft designed for the maximum achievable lifetime. This result, that is, the existence of an optimal design lifetime, disproves the implications of Eq. (13) that the customer is always better off requesting the contractor to provide a spacecraft designed for the maximum achievable lifetime. We recall that this latter conclusion was reached by considering only cost factors, namely, the monotonic decrease of the cost-per-operational-day metric as a function of the design lifetime (Fig. 4).

2) The optimal design lifetime increases as the expected revenues per day increase, for example, from 14 to 21 years as the revenues increase from \$50,000 to \$90,000/day. In other words, the more revenues customers expect to generate from a system, the longer they would want the system to remain operational. This of course is an intuitive result; Eq. (10) and Fig. 6 provide a quantitative basis for it.

3) In Fig. 7, we note that the optimal design lifetime deceases (from 8 to 3.5 years) as the expected system's time to obsolescence decreases (from 15 to 5 years). In other words, the sooner customers expect a system to become obsolete, the shorter they should require its design lifetime to be. Whereas this result is intuitive, Eqs. (10) and (16) provide a quantitative justification for it.

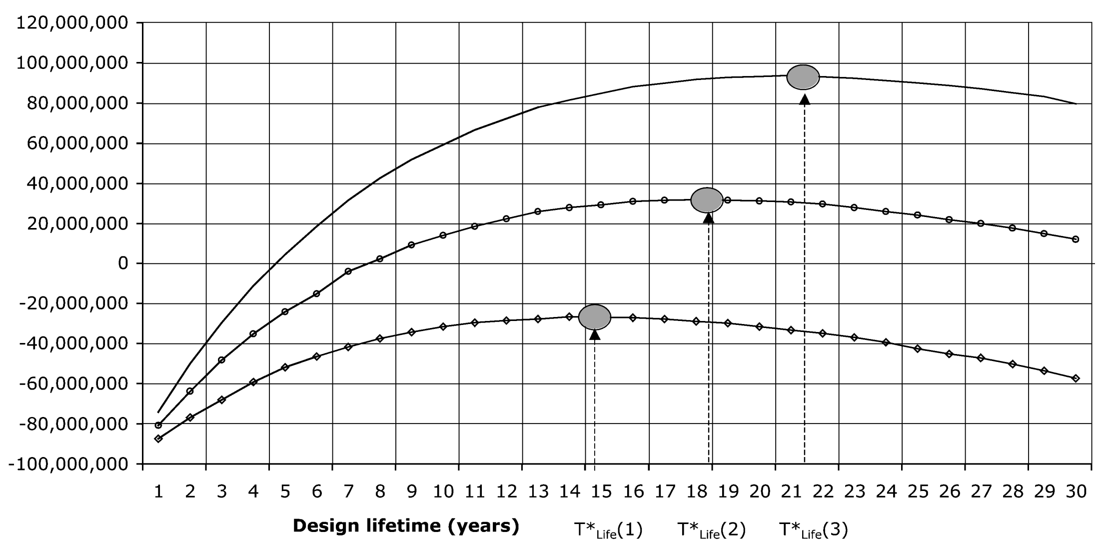

Fig. 6 Expected present value of satellite as function of its design lifetime $V(T_{\text{life}})$, assuming constant revenues per day over its design lifetime: ◇, $\mu(1)$ = \$50,000/day; ○, $u(2)$ = \$70,000/day; and ——, $u(3)$ = \$90,000/day.

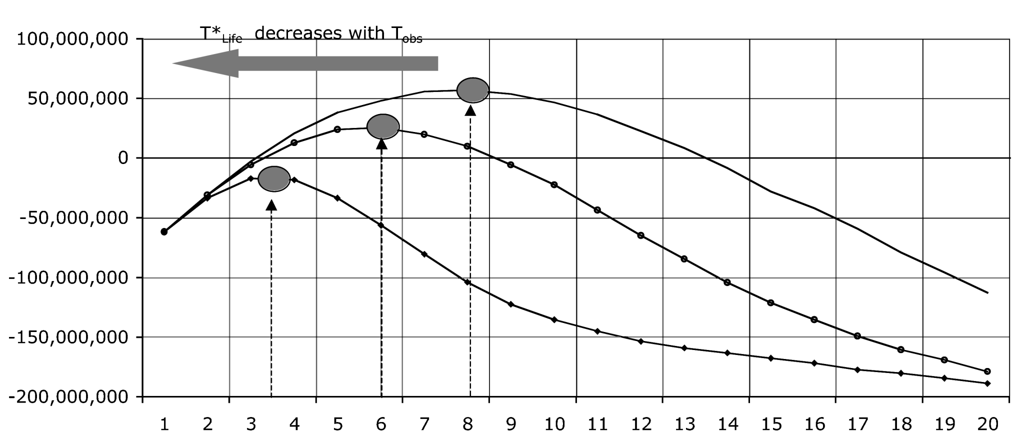

Fig. 7 Expected present value of satellite as function of its design lifetime, assuming revenues per day affected by system's obsolescence [Eq. (16)]: ◆, $T_{\text{obs}}(1) = 5$ years; ○, $T_{\text{obs}}(2) = 10$ years; and ——, $T_{\text{obs}}(3) = 15$ years.

There are a caveat and limitations: The preceding results illustrate that, under certain assumptions, satellites have optimal design lifetimes that maximize a value metric. Caution and, given the complexity of the task and analyses needed, humility are required before extrapolating these results beyond their domain of applicability. The results, however, do show the importance of undertaking the engineering, market, and financial analyses we described because their integration [Eq. (10)] can significantly impact the choice for the design lifetime of the system the customer is contemplating acquiring. More generally, our results show that intuition is not necessarily a good guide in selecting a complex engineering system design lifetime and that customers are not always better off requesting the contractor to provide a system with a maximum lifetime technically achievable.

E. Sensitivity Analysis

We now perturb the assumptions underlying the analyses discussed earlier and explore the impact on the optimal design lifetime. Four models or parameters affect the solution of Eq. (10), namely, the system's expected revenue model $u(t)$, its cost profile $C(T_{\text{life}})$, the discount rate r, and the cost per year to operate and maintain the system $\theta(t)$.

Our nominal case is the following: $u_n(t) = \$70{,}000$/day, $r_n = 10\%$, $\theta_n(t) = 10\%$ of $C(T_{\text{life}})$, and $C_n(T_{\text{life}}) = \$200$ million designed for 15 years with an average slope of 4%/year.

The results of the sensitivity analysis are shown in Fig. 8. Figure 8 reads as follows: A 10% increase in the satellite expected revenues, for instance, results in an 8.4% increase in the optimal design lifetime. Conversely, a 10% increase in the investment discount rate results in a 7.9% decrease in the spacecraft optimal design lifetime.

Given our assumptions and the nominal case considered, we find that the optimal design lifetime is most sensitive to the expected revenues of the satellite over its design lifetime $u(t)$, as well as the investment discount rate r. Equally important is the spacecraft cost profile $C(T_{\text{life}})$ and how it scales with T_{life}. Of minor importance, however, is the impact of the cost of operations $\theta(t)$ on the optimal design lifetime. These results, although illustrative, indicate where potential customers should conduct careful modeling before selecting a design lifetime for their system and where they can make do with limited accuracy of their models: Of prime importance are the market analyses and forecast of the system's expected revenue model, as well as financial analysis of the investment riskiness. Equally important are the engineering and cost estimate analyses of the system's cost profile. Of lesser importance to the selection of the design lifetime is the technical analysis and estimate of the cost to operate and maintain the system.

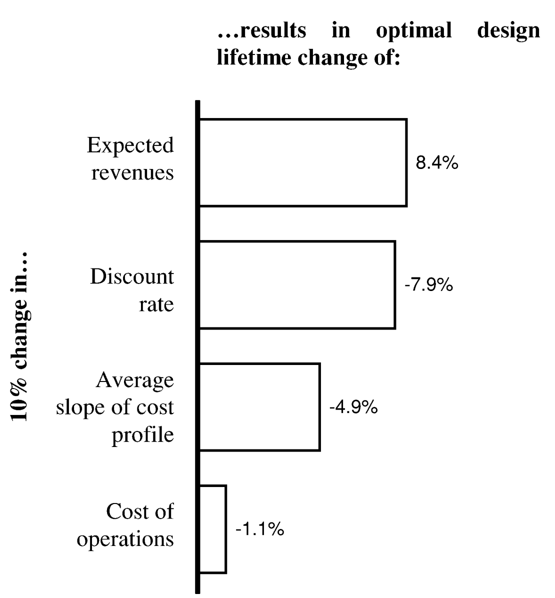

Fig. 8 Sensitivity analysis of optimal design lifetime to variations in underlying models and assumptions.

IV. Are Satellite Manufacturers Driving Themselves Out of Business by Designing for Increasingly Longer Lifetime?

The discussion about optimal design lifetimes in the preceding sections was conducted from a satellite operator's perspective. What about the manufacturers? Satellites are the lifeblood of the space industry, and it is only fitting to ask how does increasing or decreasing their design lifetime affect the manufacturers (and the launch services), not only the operators.

The results in this section are preliminary; nevertheless, they make a strong case for the spacecraft design lifetime as a powerful yet overlooked lever that can significantly impact the entire space enterprise value chain.

A. Adapting Augustine's First Law of Impending Doom to Commercial Space Sector

Norman Augustine, former chairman and chief economic officer of Lockheed Martin, half jokingly calculated that the cost of a tactical fighter would quadruple every 10 years, and that by 2054, the entire defense budget would be able to purchase just one aircraft. We contend there is somewhat similar dynamics in the commercial space sector, a geometric increase in satellite capability that will herald the second law of impending doom of the commercial space sector. What are these dynamics and what is the second law of impending doom?

Over the past 10 years, communications satellites have continued to grow in terms of size, power, and design lifetime. The average number of transponders [36-MHz transponder equivalent (TE)], for example, has increased from 26 in 1992 to 48 in 2002. The increase in power and design lifetime is shown in Table 2, where the compounded annual growth rate (CAGR) is given as a percentage (data source, Futron Corporation[11]).

The increase in number of transponders onboard a spacecraft, along with enhanced data compression techniques and increase in design lifetime have contributed to make satellites ever more powerful. According to the Futron Corporation, "the average satellite of today is approximately 900% more capable than the average satellite launched in 1990. In other words, the average satellite launched today is doing the equivalent work of 9 average satellites launched in 1990."[11] Assuming this trend will maintain its momentum, we can state our second law of impending doom of the commercial space sector: The capability of a communications satellite doubling every 4 years, the entire demand for satellite services and bandwidth in 2021 will be satisfied by just one satellite.

B. Space Sector Financial Scorecard

There is a large discrepancy in the financial performance of the different players in the space industry value chain. We consider in this section only the satellite manufacturers, launch services, and satellite operators. Equipment manufacturers, end users, insurance companies, regulatory agencies, and others who play a role in the space industry value chain are not discussed here.

Myriad metrics describe the financial performance and outlook for a company or an industry; we choose for this section a reduced financial scorecard with two measures: the sector's revenue growth over the past five years as well as its operating profitability or earnings before interest, taxes, depreciation, and amortization (EBITDA) margin. These two measures provide a good indication of the sector's past financial performance, as well as its financial attractiveness, outlook, and valuation.

The results are shown in Fig. 9 (data sources, Futron Corporation[12,13] and IDATE[14]). They merely confirm what is already known in the industry.

Table 2 Trend in GEO satellite size, power, and design lifetime[11]

Spacecraft attribute	1992	2002	CAGR (1992–2002), %
Average number of 36-MHz TE	26	48	6.3
Average power level	2.2	7.6	13.2
Average design lifetime	8	14	5.8

1) Satellites are cash cows for the operators. Satellite operators are posting excellent profitability compared to any other economic sector. In fact, the EBITDA margins we found show little variation and have been hovering over the past 5 years between 70 and 80% (for example, AsiaSat, EutelSat, IntelSat, PanAmSat, and SES Global).

2) The combined effect of several factors has decreased the demand for GEO satellites and dramatically limited the growth potential as well as the profitability of satellite manufacturers and launch services. Among those factors, first and foremost, there is the substantial overcapacity in satellite manufacturing and launch services. This overcapacity is driving a heightened competition among manufacturers, putting downward pressure on prices and allowing operators to set aggressive terms and conditions for procurement. All of these effects result in the very small margin we see in Fig. 9. The relatively flat demand for GEO communications satellites results from another set of factors: On the one hand, there is no, or not yet, satellite application that will revitalize the market and spur demand for new satellites that can provide broadband access and compete with cable and digital subscriber line (DSL). On the other hand, there is the fact that manufacturers are designing spacecraft ever more capable, with increased number of transponders, enhanced data compression techniques, and extended design lifetime, thus limiting the need for additional spacecraft.

3) Figure 9 also suggests that the current industry structure is not sustainable and that we will likely witness consolidation, vertical integration, and/or business unit divestiture in the near future.

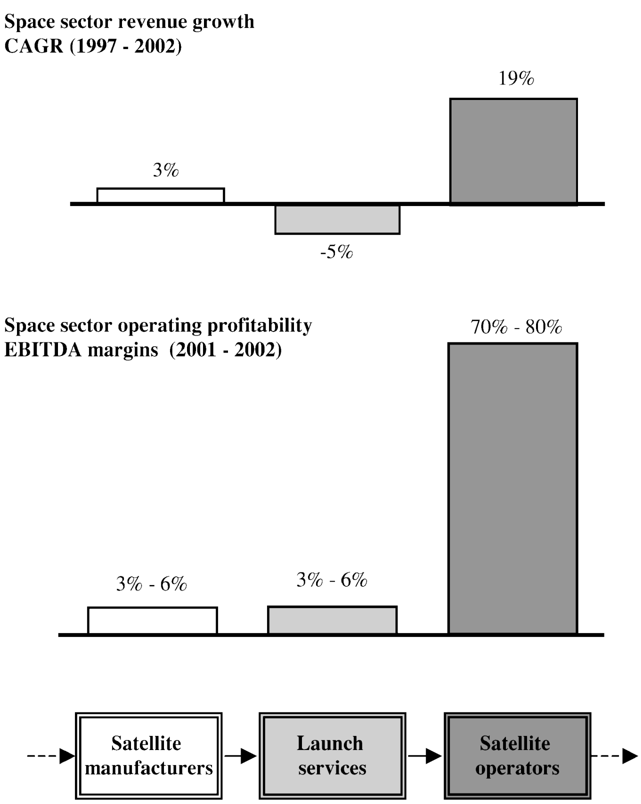

Fig. 9 Financial scorecard for key players in space sector.[12–14]

C. Design Lifetime Impact on Forecast for Satellite Orders

The satellite is the lifeblood of the space industry. Unfortunately, unlike other industries that can generate additional revenues, and higher profits, from service contracts in addition to the sale of their systems, for example, jet engines, satellite manufacturers do not have this option given the particular feature of GEO satellites of being physically inaccessible for maintenance or upgrade. On-orbit servicing, except for uploading software for upgrades or to fix on-orbit anomalies, remains to date a stalled idea of limited practicality. In Ref. 15, a comprehensive discussion of this subject matter is provided. We, therefore, are left with the number of satellites ordered as a defining metric of the industry's financial performance.

How does changing the design lifetime affect the demand for communications satellites going forward? To answer this question, the global demand for telecommunication services (telephony, video, data) must first be estimated. Second, terrestrial competition must be assessed, as well as the demand that can be captured by terrestrial networks. We are then left with the demand for satellite bandwidth, which can be translated into demand for actual satellites given the inputs of satellite size (number of transponders), utilization rate, and design lifetime. There are numerous financial analysts' reports, as well as consulting companies that provide the data for the first and second step discussed earlier. We have relied in this section on the forecast for satellite bandwidth over the period of 2004–2012 provided by the Futron Corporation.[11] Using a design lifetime of 15 years, a use rate of 60–80%, and an average of 50, 36-MHz TEs, Futron forecasts a dramatic decline in the demand for communications satellites. The company estimates there will be a need for barely 8–15 commercial GEO satellites for the next several years. We have relied on Futron's estimate for satellite bandwidth, but we varied the design lifetime between 5 and 15 years. Our results are shown in Fig. 10, where the nominal design lifetime is set to 15 years.

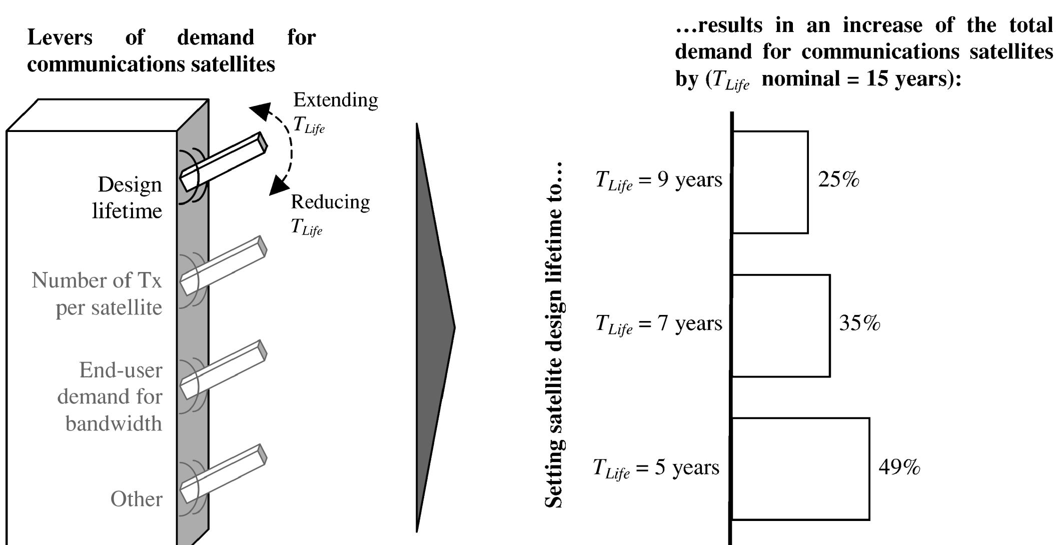

Fig. 10 Impact of design lifetime lever on total demand for communications satellite over period 2004–2012.

The results show, for instance, that, should manufacturers set the design lifetime of their communications satellites to 9 years instead of 15 years, there would be a 25% increase in the demand for communications satellites over the next several years (2004–2012), compared to demand resulting for a design lifetime set at 15 years.

Though preliminary, these results show, nevertheless, that a spacecraft design lifetime is a powerful yet overlooked lever that can significantly impact the market size for commercial communications satellites. In addition, it is likely that these results will affect the financials of the key players in the space sector and can result in a redistribution of growth and margins (Fig. 9).

V. Summary

We set up to explore the engineering and economic issues at stake for reducing or extending a complex system's design lifetime, using spacecraft as example. In the first section, we recognized that, when exploring whether there is an optimal design lifetime for complex engineering systems, it is necessary to first specify from which stakeholder's perspective the analysis is carried out because the interests and implications can be substantially different. We then synthesized and discussed the different qualitative implications associated with reducing vs extending a product's durability or a system's design lifetime, as seen from the perspective of three stakeholders, namely, the customer, the manufacturer, and society. The purpose of this qualitative discussion was to illustrate the complexity of the choice in reducing or extending a system's design lifetime, not to take a position for reducing or extending this requirement, and to lay the ground for the quantitative discussion that followed. Following the qualitative discussion, we asked whether there is an optimal design lifetime for complex engineering systems, as seen from a customer's perspective. To answer this question, we first made the case for a mindset change regarding system's design and architecture: We discussed the need, on the one hand, to view in a system the flow of service (or utility) that it will provide over its design lifetime and, on the other hand, to introduce system-level metrics as functions of time such as cost, utility, and value per unit time. Second, optimality presupposes a metric that is minimized or maximized; therefore, we proposed Eq. (1) as a means for capturing the present value of a system as a function of its design lifetime. After discussing the quantitative analyses required to answer the design lifetime optimality question, we show that, under certain assumptions, satellites do have optimal design lifetimes that maximize the value metric we introduced. These results disprove the traditional assumption that satellite operators are always better off requesting the manufacturer to provide a spacecraft designed for the maximum technically achievable lifetime. Caution, however, and, given the complexity of the task and analyses needed, humility are required before extrapolating these results beyond their domain of applicability and generalizing them to other complex engineering systems. The results, nevertheless, demonstrate the importance of undertaking the engineering, market, and financial analyses we described in this paper because their integration can significantly impact the choice for the design lifetime of the system the customer is contemplating acquiring. In the last section, we ask provocatively whether satellites manufacturers are driving themselves out of business by designing for increasingly longer lifetime. We review the trends in GEO communications satellites in terms of power, number of transponders, and design lifetime and conclude (almost seriously) that, should these trends maintain their momentum, the entire demand for satellite services and bandwidth in 2021 will be satisfied by just one satellite. More seriously, we showed that the design lifetime is a powerful, yet overlooked, lever that can significantly impact the market size for commercial communications satellites as well as the financials of the key players in the space sector.

Our main claim in this paper is that issues pertaining to the selection of an engineering system design lifetime are much more complex, and interesting, than those related to a simple product's durability and that these issues beg careful consideration and require much more attention than what they have received so far in the literature because the impact of a system's design lifetime is substantial and can ripple throughout an entire industry value chain.

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