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# Risk of spacecraft on-orbit obsolescence: Novel framework, stochastic modeling, and implications[☆]

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ABSTRACT

The Government Accountability Office (GAO) has repeatedly noted the difficulties encountered by the Department of Defense (DOD) in keeping its acquisition of space systems on schedule and within budget. Among the recommendations provided by GAO, a minimum Technology Readiness Level (TRL) for technologies to be included in the development of a space system is advised. The DOD considers this recommendation impractical arguing that if space systems were designed with only mature technologies (high TRL), they would likely become obsolete on-orbit fairly quickly. The risk of on-orbit obsolescence is a key argument in the DOD's position for dipping into low technology maturity for space acquisition programs, but this policy unfortunately often results in the cost growth and schedule slippage criticized by the GAO. The concept of risk of on-orbit obsolescence has remained qualitative to date. In this paper, we formulate a theory of risk of on-orbit obsolescence by building on the traditional notion of obsolescence and adapting it to the specificities of space systems. We develop a stochastic model for quantifying and analyzing the risk of on-orbit obsolescence, and we assess, in its light, the appropriateness of DOD's rationale for maintaining low TRL technologies in its acquisition of space assets as a strategy for mitigating on-orbit obsolescence. Our model and results contribute one step towards the resolution of the conceptual stalemate on this matter between the DOD and the GAO, and we hope will inspire academics to further investigate the risk of on-orbit obsolescence.

## 1. Introduction

The United States Government Accountability Office (GAO) has conducted over the years several detailed studies of best practices in technology development and acquisitions practices of weapon systems in general, and space systems in particular. GAO has also repeatedly noted the difficulties encountered by the Department of Defense (DOD) in keeping its acquisition of space systems on schedule and within budget. In some cases, schedules have been stretched by years, and costs have increased by millions, and in some cases billions of dollars [1]. To prevent such cost overruns and schedule slippages, GAO advised against the inclusion of low maturity technologies in acquisition programs. The DOD however disagrees with this GAO recommendation and maintains that it will continue to consider low Technology Readiness Level (TRL) technologies for inclusion in product development and acquisition—instead of keeping such technologies confined to a Science & Technology (S&T) environment until appropriate maturation. Several reasons motivate this behavior, as explained by the DOD and reported by

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## Nomenclature

| | |
|---|---|
| CRO | calendar risk of on-orbit obsolescence (dynamic) |
| DOD | department of defense |
| FTD | final total duration |
| GAO | government accountability office |
| IOC | initial operational capability |
| LRO | lifetime risk of on-orbit obsolescence (dynamic) |
| mO | minor obsolescence state |
| MO | major obsolescence state |
| $M$ | technology maturity matrix |
| $P$ | probability transition matrix of the obsolescence model |
| $p_{ij}$ | probability of jumping from state $i$ to state $j$ in a Markov chain representation |
| $p_{\Delta TRLi}$ | probability of maturing to the next TRL level $i$ within the next month |
| SoA | State-of-the-Art state |
| S&T | science & technology |
| SRO | static risk of on-orbit obsolescence |
| TRL | Technology Readiness Level |
| $TRL_{ini}$ | initial system-TRL value in the technology maturation model |
| $T_{life}$ | design lifetime of the space system |
| $t^*$ | start time of the development of a new spacecraft |
| $T_{on\text{-}orbit}$ | total time spent on-orbit by a series of spacecraft |
| $T_{SoA\ on\text{-}orbit}$ | total time spent by a series of spacecraft in State-of-the-Art while being on orbit |
| $t'$ | time axis representing the lifetime of a spacecraft |
| $t_L$ | instant of the launch of a spacecraft |
| $\tau_{ops}$ | time horizon of the risk analysis |
| $\tau_{to\text{-}orbit}$ | time needed to deploy the asset on orbit with a 95% probability |
| $X_k$ | state of the system at the discrete time $k$ in a Markov chain representation |

the GAO [2,3]. These reasons include budget constraints, schedule and organizational considerations, requirements creep (race for performance), and other aspects specific to the nature of DOD's space programs. First, conducting technology demonstration requires significant funds. As a result, the DOD maintains that low TRL technologies will continue to be included in acquisition programs, which benefits from significantly larger budgets than S&T organizations. Second, DOD's dominant position (in which "the customer does not walk away") creates an environment that is relatively tolerant of schedule slippages resulting from technology maturation issues. Furthermore, external pressures exerted by users often encourage the use of unproven technologies, which are hoped to provide significant performance benefits or highly appealing novel capabilities. A competitive environment tends to encourage this behavior, and the sometimes-inflexible performance requirements make it even more difficult to use existing and therefore more mature technology.

However, another important reason for the use of low maturity technologies in DOD's space acquisitions lies in the perception of another type of risk threatening DOD's programs. Satellites are complex systems that cannot be physically accessed after launch for possible upgrades (for the majority of them). The DOD argues that, given both their long development schedules and their long design lifetimes, satellites face a serious risk of on-orbit obsolescence if low TRL technologies are not considered at the onset of their development:

> *In view of the length of time it takes to develop space systems, DOD asserts that it will not be able to ensure that satellites, when launched, will have the most advanced technologies, unless program managers are continually developing technologies. GAO*-03-1073 [2]

Furthermore, the high pace of technological progress is such that this exposure to obsolescence can even occur before the satellites become operational.

In this paper, we focus on the risk of on-orbit obsolescence rationale for DOD's position regarding the inclusion of low TRL in acquisition programs. Our objective is to quantitatively analyze the risk of on-orbit obsolescence and assess the appropriateness of DOD's rationale for maintaining low TRL technologies in its acquisition of space assets as a strategy for mitigating on-orbit obsolescence. We hope in so doing to contribute one step towards the resolution of the conceptual stalemate on this matter between the DOD and the GAO, and to help decrease the likelihood of cost growth and schedule overruns in the acquisition of space systems.

The remainder of this paper is organized as follows. In Section 2, we provide a brief overview of the concept of obsolescence, present the implications of obsolescence in system design, and highlight the specificities of space systems to formulate the concept of "risk of on-orbit obsolescence". In Section 3, we introduce the analytical background upon which this paper is based: we first present the Technology Readiness Levels, used as a metric of technology maturity, and then provide a brief overview of Markov Chains and Monte-Carlo simulations; these constitute the analytical underpinnings of our quantitative analysis of the risk of obsolescence. In Section 4, we develop a stochastic framework and models for analyzing the risk of on-orbit obsolescence, by formulating Markov models of obsolescence and technology maturation. In Section 5, we run Monte-Carlo simulations of the models and analyze the results obtained, focusing on the influence of both the initial technology maturities and the spacecraft design lifetime on the risk of on-orbit obsolescence as well as the time of capability delivery. We finally discuss in what context the initial risk of on-orbit obsolescence can be influenced by the initial technology maturity at the start of the development of a program, and provide space organizations with guidelines to trade the risk of on-orbit obsolescence against the time of capability delivery. We conclude this work in Section 6 and we assess, in the light of the results here obtained, the appropriateness of DOD's rationale for maintaining low TRL technologies in its acquisition of space assets as a strategy for mitigating on-orbit obsolescence.

## 2. Obsolescence and the risk of on-orbit obsolescence

### 2.1. Defining obsolescence

What is obsolescence? "Obsolete" is commonly defined as "no longer in use", "of a kind or style no longer current", or "outmoded in design, style, or construction" [4]. The various manifestations of obsolescence have been studied by multiple academic disciplines. For example, in economics, obsolescence is an important problem discussed in the context of durability and depreciation [5]. In bibliometrics, obsolescence is associated with "the reduced use or decline in the use of information (on a certain topic) with time" [6]. In operations research (OR), many studies have addressed the problem of obsolescence in the context of inventory management, focusing for example on the loss of inventory value due to "sudden death" or "sudden obsolescence" (a situation, in which obsolescence is considered to occur at a point in time when market demand for a product in the inventory suddenly collapses) [7]. In a DOD context, obsolescence is defined from a supply-chain perspective and is related to the diminishing manufacturing sources and material shortages (DMSMS), which concerns "the loss or impending loss of manufacturers of items or suppliers of items or raw material" due to discontinuance of production [8]. This phenomenon, affecting electronic parts, has plagued defense programs which now rely more and more on commercial-off-the-shelf (COTS) components, and has thus become a "huge problem for designers who build systems that must last longer than the next cycle of technology" [9].

More generally, several exogenous events (e.g., technological progress, change in market needs or expectations, regulatory changes) can result in a decreasing appeal of a product or a system and thus render it obsolete. In other words, obsolescence in engineering relates the decline of the remaining value (or appeal) of a system or product over time to exogenous events.

### 2.2. Facing the consequences of obsolescence or designing against obsolescence?

The consequences of obsolescence are important and affect the commercial, scientific, and military communities. Commercial firms are evidently concerned with obsolescence as they strive to maintain their competitive advantage and attract new customers by providing them with new or improved solutions and innovative products. Scientific research highly benefits from the use of cutting edge technologies in order to address scientific and technical challenges. Finally, the consequences of obsolescence for the defense are as serious, if not more, than in a commercial context, since possessing state-of-the-art technologies is often essential to ensure strategic and tactical superiority, as well as maximizing the chances of protecting lives.

The necessity to develop strategies and methods for dealing with obsolescence is thus experienced in different environments and by the different communities (at various degrees). The efforts to address the problem of obsolescence at the engineering level have focused so far on treating the symptoms or manifestations of obsolescence (through for example replacements or upgrades of parts that have become obsolete [10]) rather than preventing obsolescence. These efforts can however come with a bundle of drawbacks and penalties: for example, as noted by Sandborn, "poor planning for parts obsolescence causes companies and militaries to spend progressively more to deal with the effects of aging systems—which leaves even less money for new investment, in effect creating a downward spiral of maintenance costs and delayed upgrades" [9].

The scarcity of academic publications on the subject reflects the absence of theoretical frameworks to assess the likelihood of obsolescence and the lack of strategic vision to avoid the decline of value of a system associated with obsolescence. The decline of value of a product due to aging (i.e., due to physical degradation) can be fairly easily addressed for example through replacement or the acquisition of a new model of the same design. In the case of obsolescence, this strategy will evidently fail since new (or newly produced) items from the same design can already be obsolete. It is therefore important to acknowledge the importance of obsolescence at the design stage of a product or system. In this paper, we propose to adopt a design-centric approach to the problem of obsolescence, by quantifying, prior to fielding, the risk of obsolescence as influenced by design choices (namely, in this article, the initial technology maturity level and the design lifetime of the spacecraft), rather than treating obsolescence (and the consequences) after it occurs. Understanding and estimating the risk of obsolescence constitutes therefore a first step towards a preemptive strategy for dealing with this important issue in engineering and system design.

In the following, we focus particularly on space systems, and briefly discuss why some of the specificities of these systems make the issue of obsolescence more critical and challenging to address.

### 2.3. Obsolescence of space systems: the concept of on-orbit obsolescence

First, most space systems are not accessible once on orbit, making physical servicing for maintenance and upgrade impossible after launch. This trait of space systems reinforces the importance of a carefully thought obsolescence mitigation strategy during the development of a spacecraft. Second, as manufacturing and launch costs represent a significant fraction of the total mission cost, current design practices tend to push towards the longest technically achievable design lifetimes. The rationale for such a choice is twofold: (1) to operate the costly asset for a long period of time to recover its cost; and (2) given the marginal cost of durability of spacecraft [11], it is always cheaper on a cost per day basis to extend the design lifetime of a spacecraft, and as a result, it has been assumed that launching spacecraft with the longest design lifetime possible ensures the highest return on investment in a space system. This logic has been shown to be flawed under certain conditions [12], and unfortunately it dramatically increases the risk of obsolescence, as space systems cannot be upgraded during their long lifetime on orbit while new technologies, and new market needs emerge on shorter time scales. Finally, the high degree of complexity of space systems requires long development schedules, typically several years. Once again, this increases the likelihood that new technologies and new market needs may appear before the completion of the spacecraft development, or that substitute products may render the spacecraft obsolete. Furthermore, the high degree of complexity of spacecraft makes it even more difficult to make changes to the original design during the development, should new technologies appear and be considered for inclusion in the design.

On-orbit obsolescence can thus be defined as the decline of the remaining value (or appeal) of a spacecraft and the services it provides on orbit, as a result of exogenous events, such as the emergence of outperforming technology (i.e., technological obsolescence) or changes in customers' needs. Given the specificities of spacecraft mentioned previously, on-orbit obsolescence is both a special case of the theory of system obsolescence, and a fundamental distinctive problem that puts the value of spacecraft at risk and that cannot be handled by the traditional reactive mitigation strategies (because of physical inaccessibility).

The importance of obsolescence for space system design is indeed increasingly recognized, not only by the DOD (as discussed previously), but also by NASA and its contractors. The risk of obsolescence is especially acute for electronic parts onboard a spacecraft, for which technological progress is particularly rapid. While electronic products acquired through a COTS approach offer reduction in production times and significant cost savings, they expose the spacecraft to an increased risk of obsolescence. This dilemma is experienced for example by engineers working on the avionics of NASA's Orion spacecraft, who describe obsolescence as a "huge challenge" and "the biggest problem [they] face", as these spacecraft are intended to "last 30 years with products that become obsolete in five years" [13]. While this case illustrates a form of logistical obsolescence (where procurement of parts becomes impossible due to discontinuation of production [14]), this situation also reflects the discrepancy between the short duration of product procurement lifecycles and the long design cycles of space systems. Within the lifetime of a space system, more technologically advanced parts are likely to emerge and result in a loss of value of the spacecraft on orbit. It appears therefore essential to consider the risk of obsolescence from the very first stages of the design of a spacecraft (i.e., upstream in the design process rather than leaving it as an afterthought), and to alter design decisions based on the desired level of acceptance of this risk.

Despite the growing awareness of the implications of obsolescence in the space community, no academic research has so far approached the problem from a system theoretic perspective. In this work, we propose to fill this gap by formulating a theory of on-orbit obsolescence and developing analytical models for quantifying and analyzing this risk. As the exogenous events that can result in the obsolescence of a space system (e.g., technological innovation, change in demand) and the time needed to develop such a system are non-deterministic, stochastic methods should be used. Our proposed stochastic framework for quantifying and analyzing the risk of on-orbit obsolescence builds on the concept of Technology Readiness Level (TRL) and consists of two Markov models: one model driving obsolescence, and one model driving technology maturation and spacecraft development. The two models are simultaneously run through Monte-Carlo simulations to quantify the risk of on-orbit obsolescence. In the following section, we provide the background information on TRL, Markov chains, and Monte Carlo simulation, before we discuss our models and analysis in Sections 4 and 5.

**Table 1**
Summary of different Technology Readiness Levels.

| TRL | Summary description |
|---|---|
| TRL 1 | Basic principles observed and reported |
| TRL 2 | Technology concept and/or application formulated |
| TRL 3 | Analytical and experimental critical function and/or characteristic proof-of- concept |
| TRL 4 | Component and/or breadboard validation in laboratory environment |
| TRL 5 | Component and/or breadboard validation in relevant environment |
| TRL 6 | System/subsystem model or prototype demonstration in a relevant environment (ground or space) |
| TRL 7 | System prototype demonstration in a space environment |
| TRL 8 | Actual system completed and "flight qualified" through test and demonstration (ground or space) |
| TRL 9 | Actual system "flight proven" through successful mission operations |

$$\begin{array}{cc|cccc|l} & & & & \text{To} & & \\ & & S1 & S2 & S3 & S4 & \\ & S1 & p_{11} & p_{12} & p_{13} & p_{14} & \\ & S2 & p_{21} & p_{22} & p_{23} & p_{24} & \\ \text{From} & S3 & p_{31} & p_{32} & p_{33} & p_{34} & = P \\ & S4 & p_{41} & p_{42} & p_{43} & p_{44} & \end{array}$$

**Fig. 1.** Transition matrix for a system with four states.

## 3. Background for the modeling and analysis of the risk of on-orbit obsolescence: TRL, Markov chains, and Monte-Carlo simulations

### 3.1. Technology Readiness Levels

The Technology Readiness Level (TRL) is a widely adopted metric by NASA and the DOD. It was introduced by NASA in the 1980s, first to assess the maturity of a particular technology before its implementation in a system, and second, to allow the "consistent comparison of maturity between different types of technology" [15]. This metric is organized on a scale of nine levels corresponding to key stages of development of a given technology. A brief description of these levels is provided in Table 1; the reader is referred to Mankins [15] for a more detailed description of these levels.

### 3.2. Markov chains

One powerful theoretical framework frequently used to model stochastic behaviors is the Markov chain. Markov chains are based on a state representation of a system in which the next future state depends only on the current state and not on the previous history of the system (this assumption is referred as the Markov property). Mathematically, a discrete-time Markov chain $\{X_n|n=0,1,\ldots\}$ is defined as a discrete-time, discrete-value random sequence such that given $X_0,\ldots,X_n$, the next random variable $X_{n+1}$ depends only on $X_n$ through the transition probability expressed in Eq. (1):

$$\Pr\{X_{n+1}=j|X_n=i,X_{n-1}=i_{n-1},\ldots,X_0=i_0\}=\Pr\{X_{n+1}=j|X_n=i\}=p_{ij} \quad (1)$$

where $X_k$ represents the state of the system at the discrete time $k$, and $p_{ij}$ is the conditional probability to transition from state $i$ to state $j$. Eq. (1) states that the probability of transitioning from state $i$ to state $j$ applies anytime the system is in state $i$ regardless of how it got there. For a Markov chain with a finite number of states, the transition probabilities from one state to the next can be expressed in the one-step transition matrix whose elements are the $p_{ij}$ coefficients. Fig. 1 shows an example of a transition matrix for a system with four states.

This matrix can be read as follows: each row refers to the current state of the system, while each column refers to the future state of the system after the transition. Since the system can only be in one state at a given time, (whether it is transitioning to a new state or staying in the current state), the sum of the probabilities along a row is equal to 1. A common representation of a Markov chain is a directed graph with nodes representing the states of the system, connected by arcs representing the possible transitions between those states, along with their probabilities. An example transition diagram of a system with four states is provided in Fig. 2.

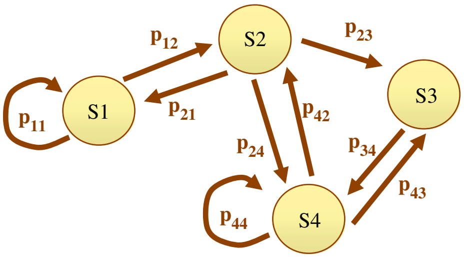


**Fig. 2.** Typical transition graph for a Markov chain.

Markov chains have been used in a wide variety of contexts and for different applications in health care [16], economic valuation [17], and reliability analysis [18] to name a few. More information about Markov chains can be found several textbooks including [19–21].

### 3.3. Monte-Carlo simulations

Performing estimation and risk analysis in the presence of uncertainty requires a method that reproduces and propagates the random nature of certain inputs (such as time to failure of various components in the context of reliability theory) in an analytical model. A Monte-Carlo simulation addresses this issue by running a model many times (e.g., thousands of times) and picking values from predefined probability distributions at each run [22].

In this work, we conduct Monte-Carlo simulations of the Markov chains representing the state of obsolescence (resulting from exogenous events) and the state of technology maturity of a space system. These Markov chains are discussed in Section 4. The probabilistic nature of these models is directly used to feed the Monte-Carlo simulations. In our case, the randomness of the process results from the multiple applications of the transition matrix of the Markov models over time. Depending on the current state of the Markov chains, the models "select" the next state according to a probability mass function that corresponds to a row of the transition matrix. We are interested in the evolution of the risk of on-orbit obsolescence over time, and therefore define a time-horizon for our analysis that we denote by $\tau_{ops}$. The Markov models stop running when the time-horizon is reached, i.e., when $t=\tau_{ops}$. Different results will thus be obtained for every run once the time-horizon is reached. It is the repetition of these runs that constitutes a Monte-Carlo simulation from which useful statistics are computed, as discussed in the following section.

## 4. Stochastic model of on-orbit obsolescence

The stochastic model of on-orbit obsolescence is composed of two models running in parallel, in order to capture the impact of the initial maturity level at start of development (initial TRL) on the likelihood of obsolescence once the spacecraft is in orbit. Both models work in discrete time, and the unit of time here considered is one month. The first is an obsolescence model, and the second is a technology maturation model. These two models are discussed next.

### 4.1. Obsolescence model

In this representation, the space system can be in one of the following three states at a time: (1) State-of-the-Art (SoA), (2) minor Obsolescence (mO), or (3) Major Obsolescence (MO). The meaning of the states is flexible and context-dependant. Consider for example a spacecraft composed of one main instrument for Earth observation. The minor Obsolescence state could correspond to the emergence of a competing technology enabling for example to double the accuracy/resolution of the observation. The Major Obsolescence state would then correspond to the emergence of a novel technology that provides an order of magnitude better accuracy/resolution. The evolution of the system over time is by construction probabilistic. The transitions of the system can be uniquely represented by a transition matrix $P$, as shown in Eq. (2):

$$P = \begin{bmatrix} p_{11} & p_{12} & p_{13} \\ 0 & p_{22} & p_{23} \\ 0 & 0 & p_{33} \end{bmatrix} \qquad (2)$$

$p_{12}$ is the probability of transitioning from the state 1 (SoA) to the state 2 (mO), $p_{13}$ is the probability of transitioning from the state 1 (SoA) to the state 3 (MO), and finally $p_{11}$ is the probability of staying in state 1 (SoA). We assume that the system cannot be upgraded (which is typical of most traditional spacecraft currently designed). Therefore, it cannot return to a more “up-to-date” state if it has become obsolete, which in turn makes the transition matrix $P$ upper-triangular and the Major Obsolescence state an absorbing state ($p_{33}=1$). The behavior of this Markov model is represented by the state diagram shown in Fig. 3.

Note that the obsolescence model is defined at the system-level, that is, each state of the Markov chain represents a state of the entire spacecraft. Conceptually, the system obsolescence states are contingent on the aggregate states of obsolescence of each individual component or subsystem (in the previous example of an Earth observation spacecraft, we considered a simple case of a spacecraft with a single instrument). Among the set of spacecraft components that are subject to obsolescence, electronic parts (as mentioned in Section 2.1) become obsolete relatively fast compared for example with thermal elements/subsystem of the spacecraft, due to rapid technological improvements in the field. The mean-time-to-obsolescence of critical electronic components of spacecraft is on the order of 3 years for digital signal processors (DSP), 6 years for logic families, and up to 8 years for linear interfaces [23]. In the obsolescence model, the transition probabilities to obsolete states have therefore been selected to yield a mean-time-to-obsolescence for the entire spacecraft that falls within the range of these values. However, it is important to acknowledge that the definition of an “obsolete spacecraft” should not be restricted to the obsolescence of one particular electronic component. Since the relationship between component-centric obsolescence and system-centric obsolescence is beyond the scope of this work, the values of the transition probabilities selected as inputs of the obsolescence model provide a first-order level of fidelity that is sufficient for the analysis of “trends” of spacecraft obsolescence conducted in this paper.

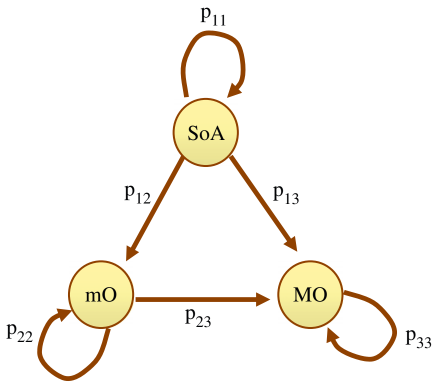


**Fig. 3.** State representation of the obsolescence model.

### 4.2. Technology maturation model

A major reason cited by the DOD to include low TRL technologies in the development of a spacecraft is that more mature technologies might become obsolete by the time the space system is launched. A key element driving this dilemma is thus the temporal competition between the pace of technology maturation and the pace of obsolescence progression. This dilemma is further exacerbated given the current typical duration spacecraft development (several years) and spacecraft design lifetime (10+ years). It is therefore critical to implement a model of technology maturation describing the time needed to mature all the technologies considered for inclusion in a space system and to ultimately bring said system to initial operational capability (IOC). We will use the notion of “system-TRL” to represent the level of maturity of the entire spacecraft, as defined by a weighted average of all its components’ TRLs (more details can be found in [24]). For example, a system TRL of 4 represents spacecraft developed under a technology demonstration program, which includes one or several technologies at a relatively low TRL (around 4); by contrast, a system TRL of 8 corresponds to a spacecraft containing very few technologies that are still unproven.

In Dubos et al. [24], we proposed a model of duration of spacecraft development as a function of the system-TRL, derived from a data set of 28 NASA missions. The model of final total duration (FTD) provides an estimate of the total time needed to complete the development of a spacecraft and launch it, given its initial system-TRL value. In this work, the model developed in [24] is applied recursively to estimate the time needed to transition from a given system-TRL value to the consecutive one. Table 2 summarizes the values obtained when conducting this process. For example, historical data show that the average time needed to develop a spacecraft with an initial system-TRL of 5 is around 78 months, while it is only 61 months for a system-TRL of 6. We then use the difference ($78-61=17$ months) as a proxy for the mean time needed to transition from system-TRL 5 to 6. These values constitute a reasonable starting point given the

**Table 2**
Technology maturation model parameters.

| System-TRL at start of spacecraft development | Average final total duration (FTD) from model (months) | Mean time needed to reach next readiness level (months) | Probability of reaching next readiness level in the next month |
|---|---|---|---|
| 4 | 100.9 | 22.3 | $p_{\Delta TRL5}=0.0448$ |
| 5 | 78.6 | 17.4 | $p_{\Delta TRL6}=0.0575$ |
| 6 | 61.2 | 13.6 | $p_{\Delta TRL7}=0.0735$ |
| 7 | 47.6 | 10.5 | $p_{\Delta TRL8}=0.0952$ |
| 8 | 37.1 | 8.2 | $p_{\Delta TRL9}=0.122$ |
| 9 | 28.9 | 6.4 | $p_{\Delta TRL9+}=0.156$ |
| 9+ | 22.5 | N/A | N/A |

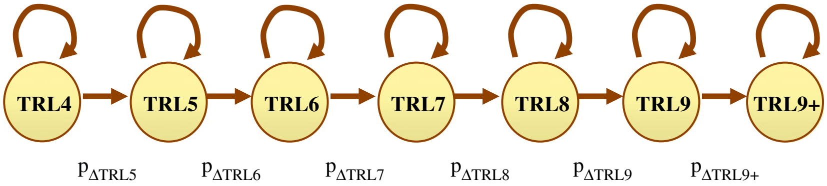


**Fig. 4.** State representation of the technology maturation model.

limited data (publicly) available on technology maturation for space systems. The specific numerical values here used can be easily refined should more data become available in the future.

The resulting model associated with these constants is Markovian as well, the states being the different levels of maturity: {TRL4, TRL5, TRL6, TRL7, TRL8, TRL9, and TRL9+}. At each time step (i.e., every month), the system has a probability $p_{\Delta TRLi}$ of maturing to the next level $i$ or staying in the same state $(i-1)$. The state "TRL9+" corresponds to a system that has already been flown and for which the technology does not need to be matured in a strict sense. The time needed to bring such a system to IOC (i.e., to deliver it to its final orbit) is assumed to be incompressible, since there is a minimum time needed to physically develop, ship and launch a spacecraft, independently of its maturity. A constant value of 22.5 months (which is the final value of the FTD corresponding to the level TRL9+) is therefore added at the end of the maturation process, after which the system is considered to be at IOC (delivered on orbit). The transition matrix $M$, or technology maturity matrix, describing this process is a band-matrix, as shown in Eq. (3), since a system can only transition to the consecutive TRL or stay at the current one:

$$M=\begin{bmatrix} 1-p_{\Delta TRL_5} & p_{\Delta TRL_5} & 0 & 0 & 0 & 0 & 0 \\ 0 & 1-p_{\Delta TRL_6} & p_{\Delta TRL_6} & 0 & 0 & 0 & 0 \\ 0 & 0 & 1-p_{\Delta TRL_7} & p_{\Delta TRL_7} & 0 & 0 & 0 \\ 0 & 0 & 0 & 1-p_{\Delta TRL_8} & p_{\Delta TRL_8} & 0 & 0 \\ 0 & 0 & 0 & 0 & 1-p_{\Delta TRL_9} & p_{\Delta TRL_9} & 0 \\ 0 & 0 & 0 & 0 & 0 & 1-p_{\Delta TRL_{9+}} & p_{\Delta TRL_{9+}} \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \quad (3)$$

The state diagram of this Markov model is shown in Fig. 4.

### 4.3. Initial conditions

The TRL value at the start of development of the spacecraft, $TRL_{ini}$, represents the level of "innovativeness" of the spacecraft, and is therefore indicative of the time needed to complete its development, as described in Table 2. This value, which is an input of the technology maturation model, can be tuned to reflect the type of scenario investigated. For example, common practices of DOD correspond to a value of $TRL_{ini}=4$ at the start of the spacecraft development, while the GAO recommends starting the development of the spacecraft with a value of at least $TRL_{ini}=7$ [3].

The initial state for the obsolescence model also depends on the initial value of the technology maturity $TRL_{ini}$. For all systems starting at the lowest TRL value in our model, $TRL_{ini}=4$, the initial obsolescence state is considered to be State-of-the-Art. Indeed, a value of 4 corresponds to technologies that are just being validated in a laboratory environment [15]. Systems starting with higher values of TRL are not necessarily obsolete, however it appears important to account for the longer history of their technology development (compared to systems with $TRL_{ini}=4$), which increases their initial exposure to obsolescence. In other words, since they have already matured for a longer period, they start with a higher initial risk of obsolescence. For a single run of the model (i.e., one spacecraft), it translates into the choice of an initial obsolescence state. This is computed probabilistically by running the obsolescence model while technology matures outside of the spacecraft, from the lowest value TRL=4 until the desired value of $TRL_{ini}$ at which technologies start being included in the spacecraft. In a statistical sense, this process ensures that for $TRL_{ini}=4$, all spacecraft start being developed while being State-of-the-Art, whereas for higher values of $TRL_{ini}$, their initial state is distributed among the three possible obsolescence states, reflecting a higher initial risk of obsolescence.

### 4.4. *Simulations*

Both the technology maturation and obsolescence models are run simultaneously. The clock starts ($t=0$) with the onset of a spacecraft development. At every time step, the system under development has a probability of transitioning to the next value of the system-TRL in the technology maturation model. Similarly, it has a probability of transitioning to a minor or Major Obsolescence state depending on its current state. When the system reaches IOC (the system is then on orbit), the technology maturation model stops. At this instant, a counter *Age* is triggered which counts the length of time the system spends on orbit and the obsolescence model remains active, to compute the risk of on-orbit obsolescence.

One important parameter characterizing a spacecraft in our analysis is its design lifetime, which we denote as $T_{life}$. When the *Age* of the spacecraft reaches its intended design lifetime $T_{life}$, the spacecraft is retired. Assuming that the need for the same (or a similar) capability still exists after the retirement of the first spacecraft, a new spacecraft must be developed to ensure its succession. The development of this new spacecraft should thus be initiated *before* the retirement of the first one, so as to minimize the likelihood of a discontinuation of the service. Since the duration of the development of a spacecraft is assumed to be function of the initial system-TRL, the simulation of the development of a new spacecraft is triggered when $Age=t^*$, where $t^*$ is defined in Eq. (4):

$$\text{For a given initial } TRL_i, \quad t^* = \max[0, T_{life} - FTD(TRL_i)] \tag{4}$$

This criterion increases the likelihood that the new spacecraft will be developed and is ready to be launched when the previous spacecraft is retired. If the average time needed to develop a new spacecraft exceeds the selected design lifetime $T_{life}$, (that is, $T_{life} - FTD(TRL_i) < 0$), the new spacecraft is developed as soon as the first one is operational and on orbit, and not before (i.e., when $Age=0^+$).

We refer to the "series of spacecraft" as the sequence of spacecraft developed in order to respond to a given need, as a result of this retirement/replacement scenario. The same initial conditions (initial TRL, initial obsolescence state) are used for every spacecraft of a given series. In other words, one series corresponds to one scenario where spacecraft are initially developed using technologies that start at $TRL_{ini}$, and with a corresponding obsolescence state calculated probabilistically. The entire simulation process along with the initial conditions for one single series of spacecraft is summarized in Fig. 5.

## 5. Results and discussion

Monte-Carlo simulations are conducted to quantify the risk of on-orbit obsolescence by running the technology maturation and obsolescence models a large number of times. One single run of a Monte-Carlo simulation represents one series of spacecraft developed over the

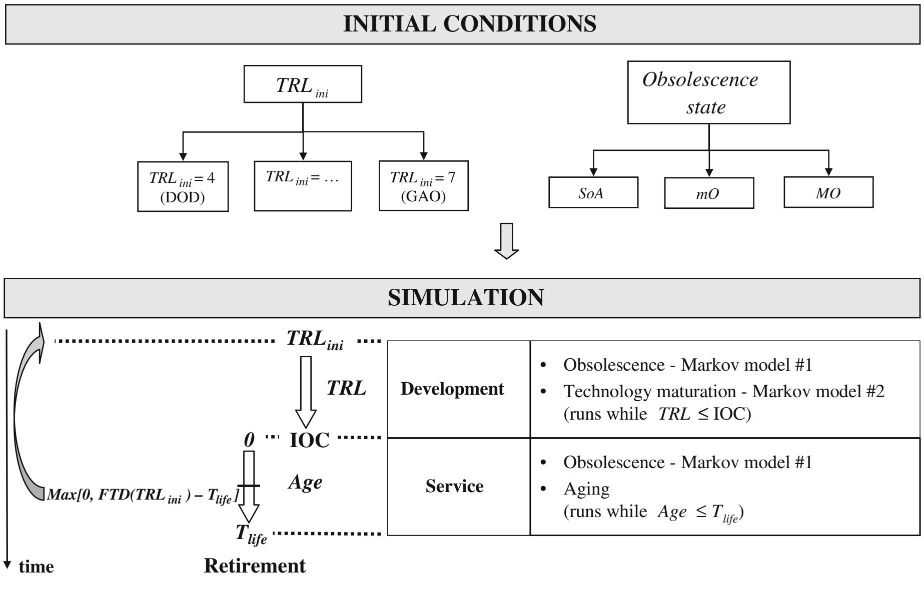


**Fig. 5.** Representation of the simulation for one single series of spacecraft.

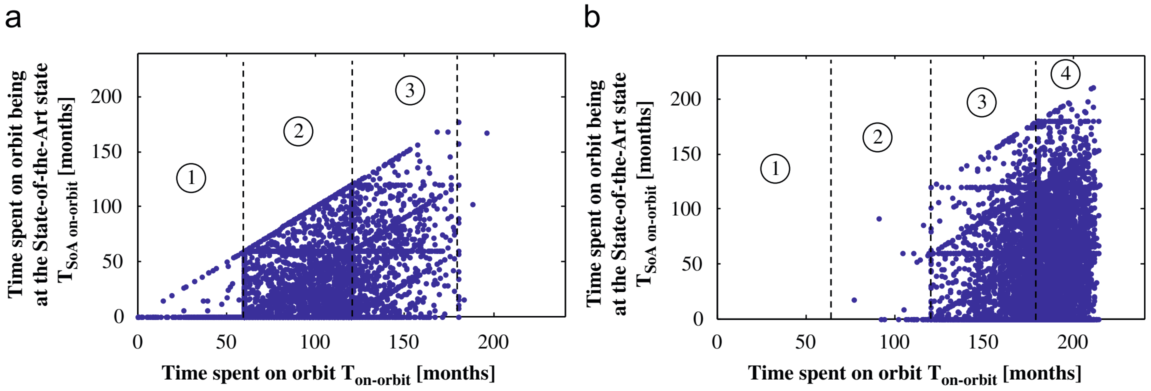


**Fig. 6.** (a) Obsolescence map for $TRL_{ini}$=4 and $T_{life}$=5 years and (b) obsolescence map for $TRL_{ini}$=7 and $T_{life}$=5 years.

time-horizon $\tau_{ops}$ (20 years or 240 months). The error of approximation in the estimates provided by the Monte-Carlo simulations, compared to the "true" quantities considered, depends on the number of cases run. The choice of the sample (or "population") size for the Monte-Carlo simulations is therefore critical to guarantee that the estimates obtained are reasonably close to the true quantities [25]. In the Monte-Carlo simulation conducted herein, the number of cases run is $n$=10,000. The resulting errors and uncertainties on the values of the estimates will be further discussed in Sections 5.2 and 5.3.

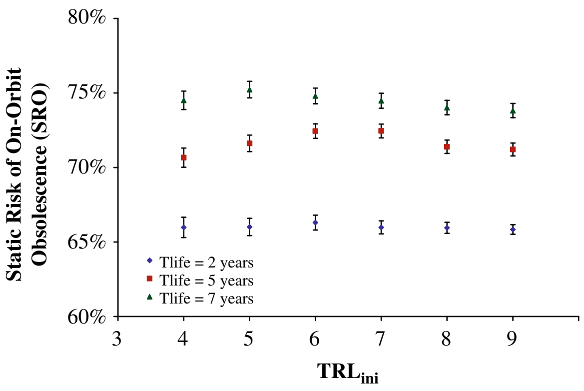


**Fig. 7.** Static risk of on-orbit obsolescence for the various values of the model parameters and corresponding 95% confidence intervals.

### 5.1. Obsolescence maps

Following the formulation of the concept of risk of on-orbit obsolescence in Section 2, it becomes intuitive that this risk depends on the time spent in an obsolete state *relative* to the total time the spacecraft is on orbit. In this subsection, we thus "observe" the time spent by the spacecraft along two dimensions: "time on orbit" versus "time in State-of-the-Art". By collecting this information for each run of a Monte-Carlo simulation, we populate an "obsolescence map", as represented on Figs. 6a and b. The $x$-axis represents the time spent on orbit for a given series of spacecraft, while the $y$-axis represents the time spent on orbit while being in the "State-of-the-Art" state. Each dot represents one run of the Monte-Carlo simulation which simulates the development of a series of spacecraft, thus including retirement/replacements over the time-horizon $\tau_{ops}$. Since for each spacecraft the time spent on orbit while being in State-of-the-Art cannot exceed the total time spent on orbit, only the lower right half of the obsolescence map is populated.

Dots on the $x$-axis ($y$=0) represent series of spacecraft that have never been State-of-the-Art (SoA) on orbit, i.e., they were obsolete as soon as they were launched. Conversely, the diagonal line ($y$=$x$) corresponds to cases in which every spacecraft developed in a given series remained State-of-the-Art for the entire duration on orbit, i.e., they were never obsolete on orbit (neither in minor nor in major obsolescence states). The closer to the $x$-axis the dots are located, the longer the spacecraft have spent while being obsolete. A few observations can be made regarding Figs. 6a and b before we delve into the statistical analysis of the simulation results:

- Different zones can be identified on the obsolescence map: for example, when $T_{life}$=5 years (60 months), zone (1) represents cases for which only one spacecraft was developed during the time horizon $\tau_{ops}$ (20 years or 240 months), while zone (2) represents cases for which two spacecraft were developed during the time horizon (thus the total time spent on orbit is between 60 and 120 months). Dots in zone (3) correspond to cases for which two spacecraft have served on orbit and been retired, and a third one has spent some time on orbit, etc.
- Since spacecraft in our model are retired after they have served their entire lifetime on orbit, and as the mean-time-to-delivery to orbit can be relatively long, most simulation cases exhibit a total time spent on orbit that is a multiple of the design lifetime $T_{life}$. This phenomenon explains the denser vertical lines between the zones, at $T_{on-orbit} = n \times T_{life}$, $n$ being an integer $\geq 1$. (This effect is more significant at low initial TRL, when the mean-time-to-delivery is long compared to the design lifetime). The $y$-axis being a "subset" of the $x$-axis, similar dense lines can be observed horizontally and on the diagonals.

- Note that zone (1) on Fig. 6a is sparsely populated except for the $y=0$ line, as it mostly represents spacecraft that required very long development times (and probably extensive schedule slippage), and that are therefore more likely to be obsolete for their remaining time spent on orbit.
- Finally, recall that the higher the initial TRL, the sooner the spacecraft are delivered (i.e., the sooner they reach IOC). This results in a longer time spent on orbit during a fixed time horizon, illustrated by a shift of the population towards higher values along the $x$-axis, as seen on Fig. 6b ($TRL_{ini}=7$), compared to Fig. 6a ($TRL_{ini}=4$).

From the Monte-Carlo simulations presented and visualized previously, it is possible to compute statistical parameters such as expected values (of time spent on orbit, or time spent in an obsolete state, etc.) and ultimately, to define various types of risks of on-orbit obsolescence, as discussed next.

### 5.2. Static risk of on-orbit obsolescence (SRO)

We define the static risk of on-orbit obsolescence (SRO) by considering the expected value of the proportion of time a system on-orbit will not spend in the State-of-the-Art state, as expressed in Eq. (5):

$$SRO = E\left[1-\frac{T_{SoA\text{-}on\text{-}orbit}}{T_{on\text{-}orbit}}\right] \tag{5}$$

Recall that a spacecraft is retired when its age reaches its design lifetime. $T_{on\text{-}orbit}$ and $T_{SoA\text{-}on\text{-}orbit}$ therefore reflect the entire time spent on orbit and in State-of-the-Art by all the successive generations of spacecraft (one entire "series of spacecraft") over the time period considered. Fig. 7 shows the static risk of on-orbit obsolescence for the different values of the model parameters, $TRL_{ini}$ and $T_{life}$. Two important results can be observed:

- *The initial technology maturity of the spacecraft has little influence on SRO*: For example, for $T_{life}=5$ years, the SRO obtained by the models is approximately 72% over a time horizon of $\tau_{ops}=20$ years, and this value remains nearly constant when $TRL_{ini}$ varies (the error bars will be discussed shortly). This result contradicts the DOD statement that systems developed from low maturity technologies will *always* be less exposed to obsolescence (we will revisit this statement in Section 5.3.2 and discuss in what specific context the initial technology maturity may influence the risk of obsolescence).
- *SRO increases when the design lifetime of the spacecraft increases*: For example, the SRO obtained by the models goes from 66% when $T_{life}=2$ years, up to 74% when $T_{life}=7$ years. This finding is not surprising since space systems characterized by a large $T_{life}$ are overall more likely to become obsolete as the development (and integration and launch) of new and competing technologies is more likely to occur over their long lifetime.

The Monte-Carlo simulation provides estimates of the SRO that are only approximations of the "true" SRO. The error $\varepsilon$ on the estimate obtained by the Monte-Carlo simulation depends on the sample size $n$ and the true standard deviation $\sigma$ of the random variable $(1-T_{SoAon\text{-}orbit}/T_{on\text{-}orbit})$, as follows:

$$\varepsilon = \frac{z_{\alpha/2}\sigma}{\sqrt{n}} \tag{6}$$

where $z_{\alpha/2}$ is the critical value of the standard normal distribution for the confidence level $1-\alpha$. (For $\alpha=0.05$, $z_{\alpha/2}=1.96$). Since the true value $\sigma$ is unknown, the sample standard deviation $s$ obtained by the Monte-Carlo simulation is used to compute the error $\varepsilon$ on the estimate [26]. For 10,000 Monte-Carlo cases, Table 3 presents the values of $s$ and the corresponding error $\varepsilon$ on the SRO for the various settings of $T_{life}$ and $TRL_{ini}$.

In all cases, the error on the estimate remains $<1\%$ point. The error bars corresponding to the 95% confidence intervals defined by SRO $\pm\,\varepsilon$ are plotted on Fig. 7. The large gap between the error bars of each series characterized by a given design lifetime $T_{life}$ suggests that the increase of the SRO as $T_{life}$ increases is statistically significant (see [27] for an interesting discussion on the use of error bars in statistical analysis).

Being exposed to various exogenous events over time, which can cause obsolescence, space systems are more likely to be obsolete as time goes by. In addition to the scalar SRO measure, other definitions of the risk of on-orbit obsolescence are therefore needed to reflect the dynamic nature of this risk. Two dynamic perspectives on and the corresponding analyses of on-orbit obsolescence are discussed next.

**Table 3**
Standard deviation $s$ of $(1-T_{SoAon\text{-}orbit}/T_{on\text{-}orbit})$ and error $\varepsilon$ on the SRO.

| $T_{life}$ (years) | | $TRL_{ini}$ | | | | | |
|---|---|---|---|---|---|---|---|
| | | 4 | 5 | 6 | 7 | 8 | 9 |
| 2 | $s$ | 0.3472 | 0.2957 | 0.2546 | 0.2224 | 0.1905 | 0.165 |
| | $\varepsilon$ | 0.006805 | 0.005796 | 0.00499 | 0.004359 | 0.003734 | 0.003234 |
| 5 | $s$ | 0.3277 | 0.2824 | 0.2482 | 0.2351 | 0.2303 | 0.221 |
| | $\varepsilon$ | 0.006423 | 0.005535 | 0.004865 | 0.004608 | 0.004514 | 0.004332 |
| 7 | $s$ | 0.3149 | 0.2814 | 0.268 | 0.257 | 0.2461 | 0.2416 |
| | $\varepsilon$ | 0.006172 | 0.005515 | 0.005253 | 0.005037 | 0.004824 | 0.004735 |

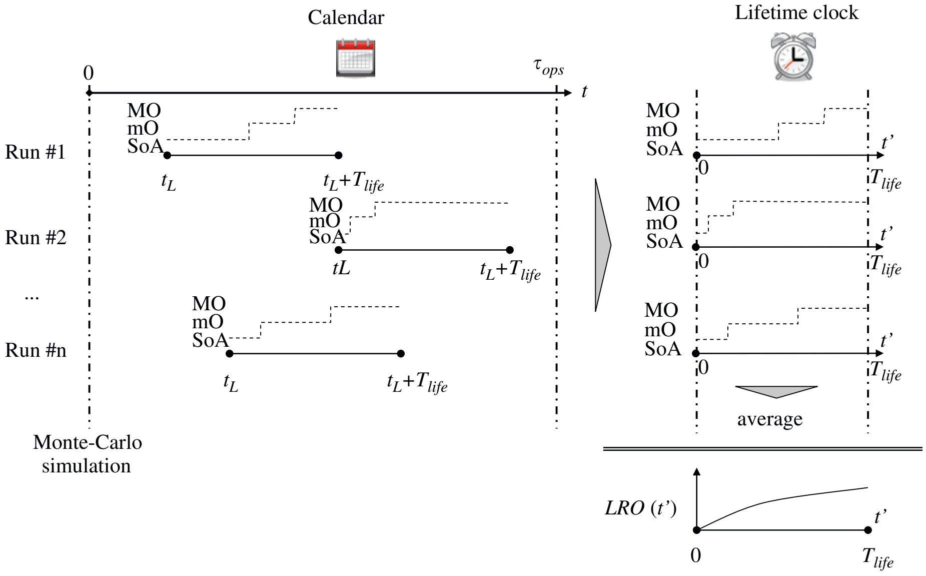


**Fig. 8.** Illustration of the calculation process of the lifetime risk of on-orbit obsolescence.

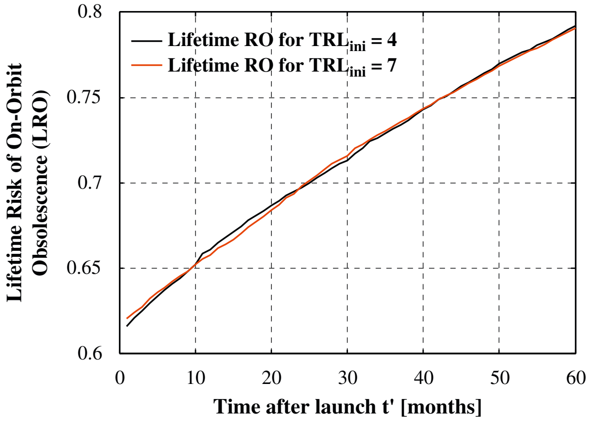


**Fig. 9.** Lifetime risk of on-orbit obsolescence for $TRL_{ini}$=4 and $TRL_{ini}$=7 ($T_{life}$=5 years).

## 5.3. Two dynamic views of the risk of on-orbit obsolescence

We propose two additional measures for the risk of on-orbit obsolescence based on instantaneous quantities (i.e., defined at every instant of time), so as to allow the study of the temporal evolution of the risk of obsolescence. A fundamental conceptual difference exists between the two measures introduced next, and involves the reference used to measure time.

For dynamic analyses conducted in the context of value-centric design, we emphasize the importance of precisely specifying the temporal mindset in which one operates. In [28], we introduced the paradigm shift needed to address issues of space responsiveness, from the traditional “clock-based mindset” (the value of a spacecraft starts being evaluated after the launch of the spacecraft, and for a given period of time after that date), to a “calendar-based mindset” (the value of a spacecraft starts being evaluated when the spacecraft development starts, in response to a need, and until a specific calendar date—in this context, a schedule slippage penalizes the value of a spacecraft). To analyze the risk of on-orbit obsolescence, which affects the value of a space system, a similar distinction can be made between a clock-based and a calendar-based design and acquisition mindset/environment. As will be discussed next, such a distinction will shed some light on the appropriateness of the key argument in the DOD’s position for dipping into low technology maturity (low TRL) in the acquisition and development of space programs (in disagreement with GAO’s recommendation of confining acquisition programs to high TRL to avoid cost growth and schedule slippage).

### 5.3.1. Lifetime risk of on-orbit obsolescence

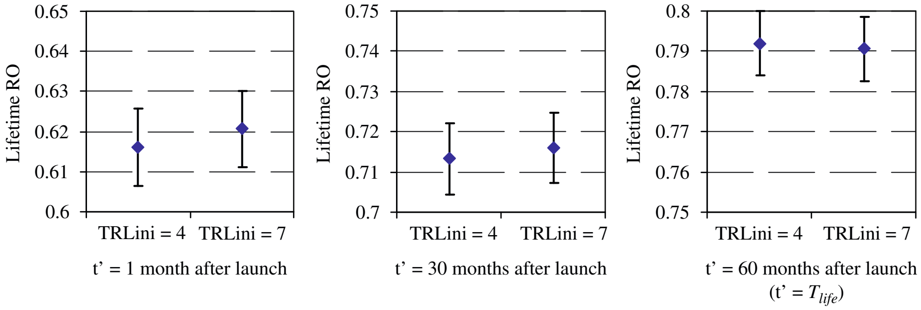
The following dynamic definition of the risk of on-orbit obsolescence fits within clock-based considerations, and aims at answering the following question:

> What is the probability that a spacecraft will become obsolete *n* years after being launched?

Since such a question is legitimate at any time during the lifetime of the spacecraft (i.e., from its launch until its retirement), we refer to this dynamic risk as the lifetime risk of on-orbit obsolescence (LRO). In this clock-based mindset where the actual calendar date, e.g., April 2010, is irrelevant, the time axis $t'$ represents the lifetime of the spacecraft, and the instant of the launch of each spacecraft $t_L$ is taken as the common time origin.

In this time referential, the lifetime risk of on-orbit obsolescence (LRO) represents the instantaneous probability of the spacecraft of being obsolete at a given instant during its lifetime:

$$LRO(t') = \Pr\{Obsolete\}(t') \tag{7}$$



t' = 1 month after launch

t' = 30 months after launch

t' = 60 months after launch ($t' = T_{life}$)

**Fig. 10.** Lifetime risk of on-orbit obsolescence and 95% confidence intervals at $t'=1$, 30 and 60 months after launch, for $TRL_{ini}=4$ and $TRL_{ini}=7$ ($T_{life}=5$ years).

In this expression, being "obsolete" corresponds to the event "not in SoA state" in the obsolescence model. The calculation of the LRO is illustrated in Fig. 8.

Fig. 9 shows the results for the lifetime risk of on-orbit obsolescence obtained with the models for two different values of the initial TRL, namely $TRL_{ini}=4$ and $TRL_{ini}=7$. The important result is that the initial level of technology maturity shows no impact on the LRO of a spacecraft. For example, the likelihood that a spacecraft will be obsolete right after being launched is the same whether the initial TRL was low (such as $TRL_{ini}=4$) or high (such as $TRL_{ini}=7$). In both cases, this initial lifetime risk is around 62%. Note that the LRO increases from the launch until the retirement of the spacecraft. For example, the likelihood that the spacecraft will be obsolete 30 months after launch is roughly equal to 72% regardless of the initial TRL.

Fig. 10 shows a "close-up" of the lifetime risk of on-orbit obsolescence for the two initial TRL values, at three points in time, namely at $t'=1$, 30 and 60 months. The corresponding 95% confidence intervals that almost fully overlap between $TRL_{ini}=4$ and $TRL_{ini}=7$ indicates the absence of statistical effect of the initial TRL on the lifetime risk of on-orbit obsolescence.

Varying the lifetime of the spacecraft also yielded similar results for the LRO (the time window considered for the analysis became larger).

Recall that by construction of the models, systems starting with a TRL of 4 have a lower initial chance of being in an obsolete state than systems with an initial TRL of 7, when their development starts. On the other hand, it takes longer to mature technologies in a spacecraft with $TRL_{ini}=4$, and to ultimately launch this spacecraft. This longer schedule eventually increases the likelihood of being obsolete after the launch, which cancels out the initial advantage at the start of development due to the lower TRL. As a result of these two conflicting trends, the argument that spacecraft whose development starts with low maturity technologies are less likely to be obsolete after launch than "high-TRL systems" appears to be flawed.

It is important to note that the quantitative results provided previously should not be over interpreted or used beyond the domain of validity of the data used to calibrate the model. The exposure to obsolescence for example may be influenced by factors inherent to the mode of production of spacecraft and that have not been directly included in this analysis.[1] More attention should therefore be given to the trends than to the absolute results generated by the models. Nevertheless, the absence of significant effect of the initial system-TRL on the lifetime risk of on-orbit obsolescence exhibited by the models appears to be of an "intrinsic" nature to the problem at hand rather than model-dependant. Since additional time is required to mature and implement technologies that are initially at low TRL, no significant reduction in risk of obsolescence is in fact obtained when such technologies are used. The idea that the risk of obsolescence is directly reduced with the use of low TRL technologies appears flawed, merely because it does not properly consider the longer schedules resulting from the use of such technologies.

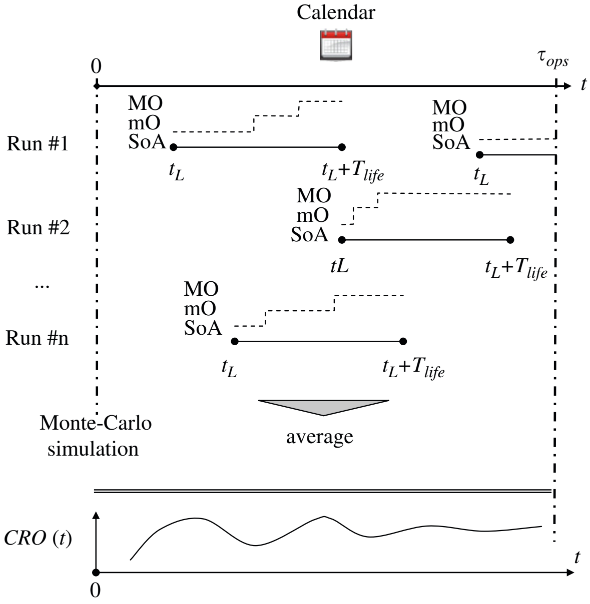


**Fig. 11.** Illustration of the calculation process of the calendar risk of on-orbit obsolescence.

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[1] The mode of production is for example different for a one-of-a-kind scientific satellite than for a production-line defense satellite (we are grateful to one anonymous reviewer for raising this point).

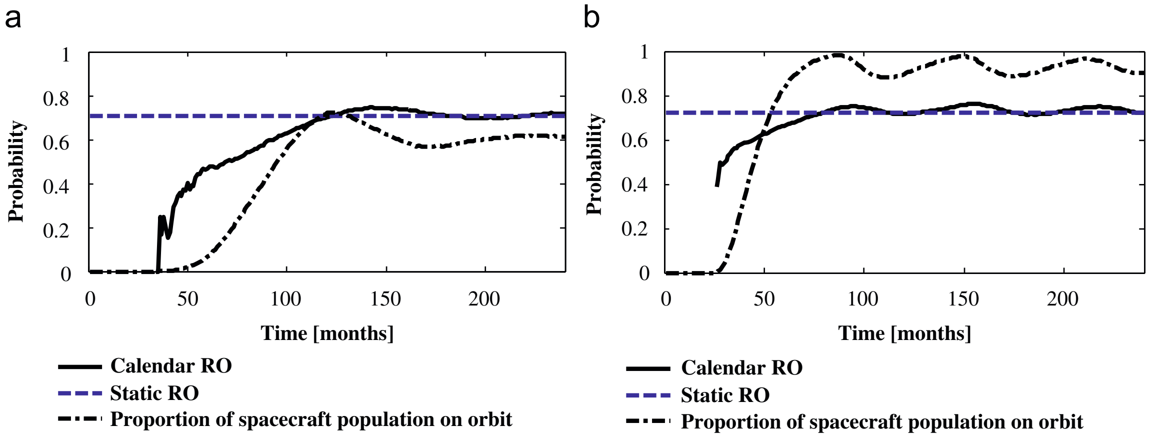

**Fig. 12.** (a) Calendar risk of on-orbit obsolescence for $TRL_{ini}$=4 and $T_{life}$=5 years and (b) calendar risk of on-orbit obsolescence for $TRL_{ini}$=7 and $T_{life}$=5 years.

Organizations with space assets, such as the DOD, may be interested, in addition to the LRO, in estimating another type of risk of on-orbit obsolescence, which focuses on a specific (calendar) date in the future. We introduce next a second dynamic risk measure, the "calendar risk of on-orbit obsolescence" (CRO).

### *5.3.2. Calendar risk of on-orbit obsolescence*

Instead of using the time origin as the moment when the spacecraft is launched, as done previously (i.e., the clock is triggered after the spacecraft is launched), we adopt in this paragraph a different time origin: $t$=0 now represents the "program decision time", that is the instant at which the development of a spacecraft is initiated, in response to a given need (i.e., the clock is now triggered once the program is initiated). Using this new time reference, one may be interested in answering the following question:

> If the development of a spacecraft starts now, what is the probability that the system will be obsolete at a given date (e.g., 2015), provided it is then on-orbit?

To address this problem, we define the "calendar risk of on-orbit obsolescence" (CRO) as follows:

$$CRO(t) = \Pr\{obsolete|on\!-\!orbit\}(t) = \frac{\Pr\{obsolete\ AND\ on\!-\!orbit\}(t)}{\Pr\{on\!-\!orbit\}(t)} \quad (8)$$

The CRO thus represents the conditional probability of the spacecraft of being obsolete, provided it is on-orbit, at a given instant (or calendar date). In this expression, being "obsolete" also corresponds to the event "not in SoA state" in the obsolescence model. In other words, the CRO represents the instantaneous risk that a *currently* operational spacecraft is obsolete. The calculation of the CRO is illustrated in Fig. 11.

Using a design lifetime $T_{life}$=5 years, Figs. 12a and b represent the calendar risk of on-orbit obsolescence for two different values of the initial system-TRL, namely $TRL_{ini}$=4 and $TRL_{ini}$=7. Also plotted on these figures is the proportion of systems in the population that are on orbit, which is an estimate of the instantaneous probability of being on orbit. At $t$=0, this proportion is zero since all systems have just started being developed. (Since it is also the denominator of the ratio defining the CRO, the small values of this probability of being on orbit explain the numerically ill-conditioned behavior of the CRO when time is close to zero. In these cases, the CRO behaves like the undefined ratio "0/0"). As more spacecraft reach IOC at different instants, this proportion increases, as can be seen on the dash-dotted curves. Several important trends can be observed:

- The static risk of on-orbit obsolescence (SRO) is the limit of the calendar risk of on-orbit obsolescence (CRO) when time goes to infinity.
- While the static RO is similar for both initial system-TRL values, the calendar risk of on-orbit obsolescence for the two systems are fairly different in their transient phase. The model shows that systems with low maturity (and thus innovative) technologies ($TRL_{ini}$=4) start at a low initial calendar RO, which is around 33% for the first systems that are delivered on orbit (Fig. 12a). Conversely, more mature systems ($TRL_{ini}$=7), start with a higher calendar RO (around 50% after the initial instability).
- The calendar RO of low technology maturity systems remains below the static limit for a longer period than that one of higher maturity systems. For example, when $TRL_{ini}$=4, the static limit of RO of 72% is first reached by the calendar RO at $t$=124 months, instead of $t$=80 months when $TRL_{ini}$=7. Stated differently, up until 124 months after the development of the spacecraft starts, low TRL systems have a lower likelihood of being obsolete than high TRL systems, if they are delivered on orbit. As mentioned in Section 5.3.1, spacecraft whose development start at low TRL have a low chance of being delivered early (as showed by the curve of the proportion of spacecraft population on orbit), but if they are, they are likely to be less obsolete

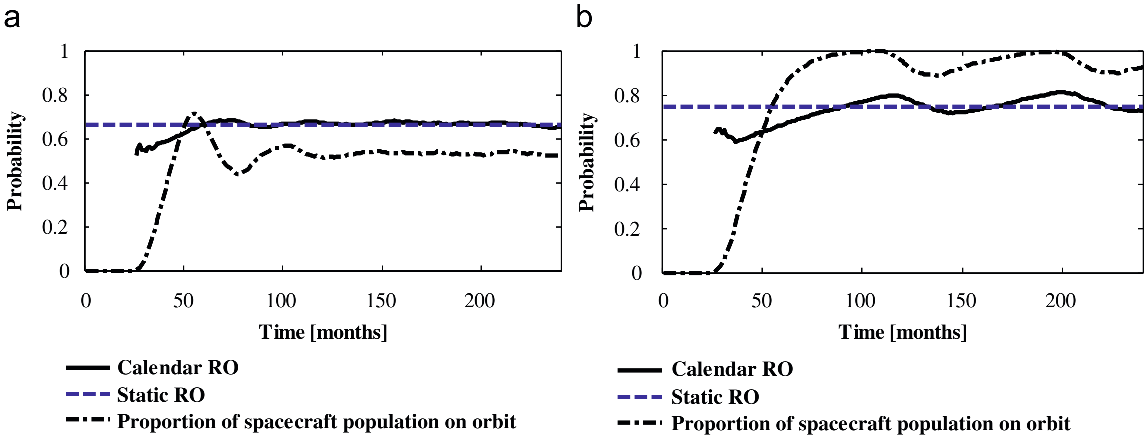

**Fig. 13.** (a) Calendar risk of on-orbit obsolescence for $TRL_{ini}=7$ and $T_{life}=2$ years, and (b) calendar risk of on-orbit obsolescence for $TRL_{ini}=7$ and $T_{life}=7$ years.

at a given calendar date after the start of their development than high TRL systems.

In short, systems with more mature technologies are exposed to a higher initial calendar risk of on-orbit obsolescence, but this disadvantage slowly vanishes over time as the calendar risk of on-orbit obsolescence converges towards the static risk of on-orbit obsolescence, which is the same regardless of the initial TRL value. Furthermore, the advantage of low maturity systems in terms of initial calendar risk of on-orbit obsolescence is obtained for the rare (low probability) scenarios where these systems are delivered early (the reader is referred to the Introduction of the present work for a discussion of schedule slippage and low TRL in space programs).

The previous analysis was conducted for a fixed $T_{life}=5$ years. Figs. 13a and b show how the behavior of the calendar risk of on-orbit obsolescence is affected when the design lifetime $T_{life}$ varies, while the initial technology maturity is held constant.

- Except for the short oscillatory transient due to the numerical artifact of the model, the calendar RO starts at the initial value of 59% around $t=36$ months in both cases, for $T_{life}=2$ years and $T_{life}=7$ years. The spacecraft design lifetime has no impact on the initial likelihood of a spacecraft to be obsolete.
- For a short design lifetime of $T_{life}=2$ years, the calendar risk of on-orbit obsolescence quickly converges to the static limit, as the proportion of spacecraft on-orbit reaches a stationary distribution. Conversely, Fig. 13b indicates that for a larger value of $T_{life}=7$ years the oscillations subsist longer, with a CRO ranging from 72% to 80%. The shorter cycles associated with shorter design lifetimes therefore result in a smaller variability of the CRO.

While the design lifetime of the spacecraft does not affect the initial calendar risk of on-orbit obsolescence, it modifies the nature of the cycles (amplitude and period) of the CRO for a series of spacecraft developed in response to a given need.

In the light of the two types of dynamic risks of on-orbit obsolescence introduced previously, it becomes important for an organization concerned with the risk of on-orbit obsolescence to understand and articulate its “temporal mindset”, as different implications and mitigation strategies result in a clock-based versus a calendar-based design and acquisition environment (the latter being the paradigm shift that space responsiveness introduces [28]). For example:

- If an organization is concerned with the likelihood that a spacecraft will be obsolete after a given period following launch, then the lifetime risk of on-orbit obsolescence is the relevant metric. The preliminary results obtained by our models indicate that the initial technology maturity level has little if any influence on this risk of obsolescence. In other words, it is ineffectual to dip into low TRL technologies with the hope of mitigating the risk of on-orbit obsolescence as the spacecraft LRO is not affected by such TRL choice. In addition, while not providing advantages in terms of LRO, low TRL increase the likelihood of schedule slippage and cost growth in spacecraft development [24,28].
- If, at the start of the spacecraft development, an organization is concerned for some reason with the likelihood that a spacecraft on orbit will be obsolete at a given date, then the calendar risk of on-orbit obsolescence is a relevant metric. Space systems with innovative technologies (still unproven and therefore at low TRL) start with an initial advantage over more mature systems. However, this advantage is only meaningful if the spacecraft are developed in a timely manner, an unlikely scenario for low maturity systems. Furthermore, this advantage disappears over time, since, for all systems, the calendar risk of on-orbit obsolescence converges towards the static risk of on-orbit obsolescence, which is the same regardless of the initial technology maturity level. It is incumbent upon

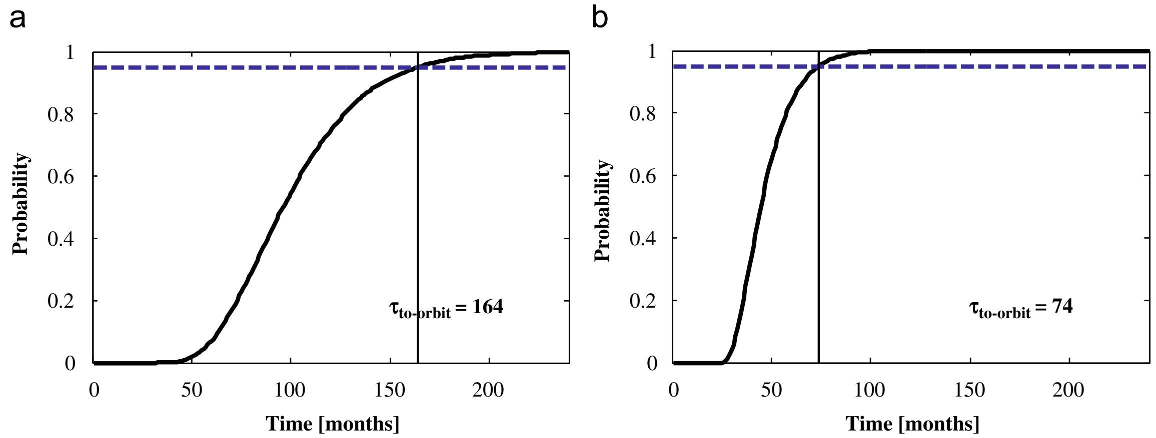

**Fig. 14.** (a) First delivery to orbit for $TRL_{ini}$=4 and $T_{life}$=5 years and (b) first delivery to orbit for $TRL_{ini}$=7 and $T_{life}$=5 years.

**Table 4**
Time-to-orbit as a function of $TRL_{ini}$.

| $TRL_{ini}$ | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|
| $\tau_{to\text{-}orbit}$ (months) | 164 | 127 | 98 | 74 | 56 | 41 |

an organization to justify or provide a convincing rationale for its interest in the calendar risk of on-orbit obsolescence; it should be understood however that a lower initial CRO can only be obtained with low maturity technologies, and thus a higher likelihood of schedule slippage.

In the following subsection, we quantify the time required to deliver a spacecraft depending on the initial technology maturity $TRL_{ini}$.

### 5.4. Time-to-orbit or time of first delivery of capability

We touched previously on another effect of including more mature technologies in space systems: the reduction of development times, which results in an earlier date of the delivery of service to the customer. By analogy with control theory, it is possible to define a time constant reflecting the time to develop and deploy the space system and deliver the desired capability, or time to "respond" to a given need. This issue, presented in Ref. [29], has become crucial as increasingly more resources are invested to develop an "Operationally Responsive Space". We denote by $\tau_{to\text{-}orbit}$ the time-to-orbit, or time of the first delivery of capability. This quantity represents the time needed to develop and deploy the asset on orbit with a 95% probability, and is defined from the start of development until the asset starts providing service to the customer. In this definition, the time-to-orbit only captures the first "cycle" of development/service of a spacecraft responding to a need, and does not consider the later replacements of retired spacecraft. The time-to-orbit is thus also the time of the first delivery of capability, which is an essential parameter indicative of space responsiveness. Recall that given an initial TRL value (representing the initial level of technology maturity of the spacecraft), the technology maturation model estimates the time needed to reach IOC. The time-to-orbit $\tau_{to\text{-}orbit}$ is thus simply computed by looking at the time needed for 95% of the cases of a Monte-Carlo simulation to reach IOC. As seen on Figs. 14a and b, the results obtained by the model for $\tau_{to\text{-}orbit}$ show that the capability is delivered approximately twice faster when $TRL_{ini}$=7 (74 months) than when $TRL_{ini}$=4 (164 months).

Table 4 shows the values of the time-to-orbit $\tau_{to\text{-}orbit}$ obtained with the models, for the various values of the initial technology maturity $TRL_{ini}$.

### 5.5. Obsolescence-responsiveness plot

The results presented previously in Sections 5.2 and 5.4 highlight the trade-off that must be considered by an organization developing space systems (such as the DOD or NASA), between the initial calendar risk of on-orbit obsolescence, if this measure of interest to them, and the time of the first delivery of the capability. This compromise is illustrated in Fig. 15: the higher the initial TRL, the higher the initial calendar risk of on-orbit obsolescence, but the faster the spacecraft will be delivered (and reciprocally).

As these two objectives are conflicting, the appropriate initial level of maturity for the technologies implemented on a spacecraft will depend on the priority given to one or the other by the decision-makers. The quantitative analysis presented in this paper can prove useful to guide such decisions. Specifically, an obsolescence-responsiveness plot can display the trade-off between time-to-orbit and initial calendar risk of on-orbit obsolescence for the different possible initial TRL values. In Fig. 16, we provide an example of such a plot for a CRO three years after the start of the spacecraft development.[2]

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[2] It is after three years that, for all values of $TRL_{ini}$, a statistically significant proportion of spacecraft is delivered on orbit, thus allowing a proper definition and calculation of the CRO.

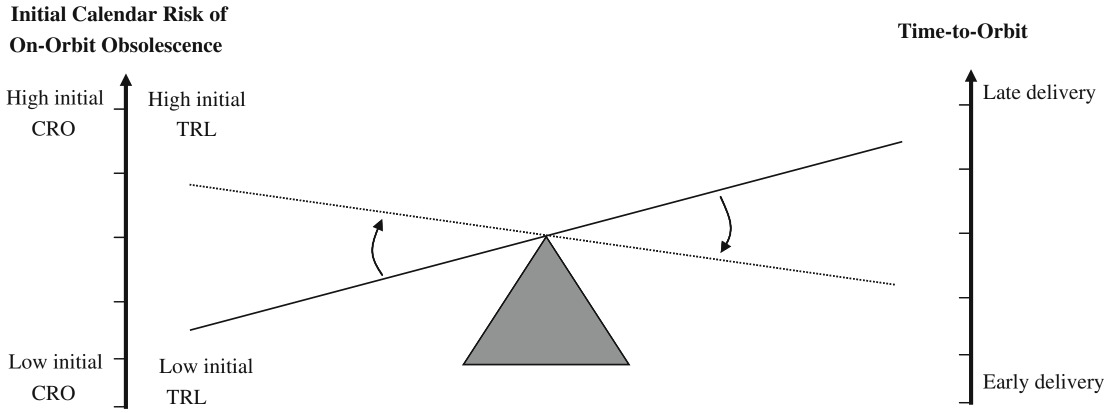

**Fig. 15.** Illustration of the trade-off between initial CRO and time of first delivery of capability.

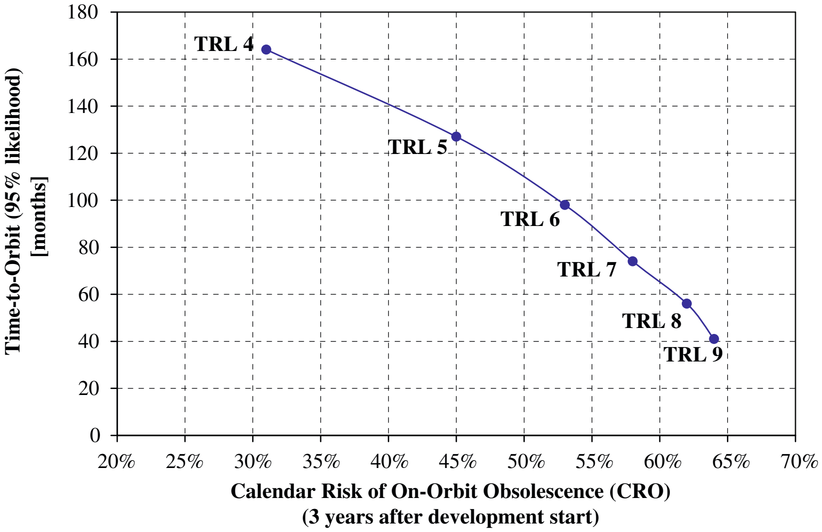

**Fig. 16.** Example of an obsolescence-responsiveness plot.

- Fig. 15 reads as follows: for example, a system with an average initial TRL=5 is likely to be delivered on orbit within 127 months and, three years after the start of the program, will likely be obsolete (or not State-of-the-Art) with a 43% chance. On the other hand, a system with an average initial TRL=7 is likely to be delivered in 74 months (faster delivery than the previous system), with an initial risk of obsolescence three years after the development start of 58% (but higher initial CRO).
- For a given schedule (or responsiveness) requirement, which can be represented in the obsolescence-responsiveness plot by a horizontal line above which the time-to-orbit should not go, the figure shows the preferred initial TRL values that will most likely satisfy this requirement. For those various design options, the different values of the initial risk of on-orbit obsolescence are then provided. For example, if a spacecraft needs to be operational within 80 months of development start, designs with an initial system-TRL of 7 and above will most likely satisfy this schedule constraint. Furthermore, the likelihood that the spacecraft will be obsolete after three years of start of development will be at least 58%.
- If for example an organization is concerned with the risk of obsolescence and only wants to fly a spacecraft that will have $<50\%$ chance of being obsolete three years after the development starts, then system-TRL $<6$ should be selected. Furthermore, the time-to-orbit of the first delivery of the capability will most likely exceed 110 months.

Caveat: it is recognized that the contribution of such a plot (Fig. 16) cannot be interpreted beyond the level of fidelity offered by the data used to generate the models of technology maturation and the obsolescence models. The example provided herein indicates trends and serves as an illustration of the trade-off between time-to-orbit and calendar risk of on-orbit obsolescence. Should more data become available regarding the time needed to mature technology, as well as empirical data on the spacecraft obsolescence (to derive the probabilities in Eq. (2)), different plots could be generated that would offer, beyond the trends here identified, an increased level of fidelity in the quantitative findings and "absolute" values of the numerical results.

## 6. Conclusion

Technology maturity has been a central argument in the diverging views of GAO and the DOD regarding best practices for the development of space systems. In several reports, GAO recommended the inclusion of only mature technologies in acquisition programs, specifically with a $\text{TRL} \geq 7$, in order to limit the likelihood of cost growth and schedule slippage. While the DOD remains committed to limiting the probability of cost overruns and schedule slippages, it is also concerned with the likelihood of deploying space assets that may become rapidly obsolete on orbit. Obsolescence can indeed reduce the ability of a defense organization to maintain its strategic and tactical superiority. This dilemma can explain in part the reluctance of the DOD to apply GAO's recommendations regarding the minimum TRL threshold. By their specificities (physical non-accessibility, long development schedule and extended design lifetimes), space systems are exposed to a unique form of obsolescence, which we referred to as the "risk of on-orbit obsolescence".

In this paper, we developed a stochastic model of risk of on-orbit obsolescence based on two Markov models, the first capturing the drift of a space asset towards obsolescence, and the second simulating the technology maturation process using system-TRL as a yardstick. The interaction of those two models, along with the description of a given spacecraft characteristics, allowed us to define several types of risks of on-orbit obsolescence. The static risk of on-orbit obsolescence represents the *overall* risk that the spacecraft used over a given time-horizon will be obsolete while being on orbit. The (dynamic) lifetime risk of on-orbit obsolescence informs us about the instantaneous probability that a spacecraft will be obsolete at a given instant after it has been launched. Finally, the (dynamic) calendar risk of on-orbit obsolescence represents the instantaneous conditional probability of the spacecraft of being obsolete, provided it is on orbit, at a given calendar date.

Through these last two definitions, we insisted on the importance of clearly defining the temporal mindset in which one operates to assess the evolution of the risk of obsolescence over time. When observed over the entire lifetime of the spacecraft (via the LRO), this risk of obsolescence is no more significant at high TRL than at low TRL. When focusing on a given calendar date (via the CRO), a lower initial risk of obsolescence can be obtained with low maturity technologies. This can however occur only in the rare eventuality of a timely delivery of the spacecraft. An obsolescence-responsiveness plot, an example of which was provided herein, can display the resulting trade-off between this initial risk of obsolescence and the time of capability delivery on orbit.

We believe the idea of risk of on-orbit obsolescence is a promising conceptual contribution, and it should be of interest to program managers and decision-makers within the DOD and in other organizations/agencies dealing with space systems. Significant research remains to be done to further explore this idea and refine the models and analytics here proposed. We invite researchers and practitioners to contribute to this endeavor, the results of which can have important impact on the current practices in space systems design and acquisition.

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