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Spacecraft Technology Portfolio: Probabilistic Modeling and Implications for Responsiveness and Schedule Slippage

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Addressing the challenges of Responsive Space and mitigating the risk of schedule slippage in space programs require a thorough understanding of the various factors driving the development schedule of a space system. The present work contributes theoretical and practical results in this direction. A spacecraft is here conceived of as a technology portfolio. The characteristics of this portfolio are defined as its size (e.g., number of instruments), the technology maturity of each instrument and the resulting Technology Readiness Level (TRL) heterogeneity, and their effects on the delivery schedule of a spacecraft are investigated. Following a brief overview of the concept of R&D portfolio and its relevance to spacecraft design, a probabilistic model of the Time-to-Delivery of a spacecraft is formulated, which includes the development, Integration and Testing, and Shipping phases. The Mean-Time-To-Delivery (MTTD) of the spacecraft is quantified based on the portfolio characteristics, and it is shown that the Mean-Time-To-Delivery (MTTD) of the spacecraft and its schedule risk are significantly impacted by decreasing TRL and increasing portfolio size. Finally, the utility implications of varying the portfolio characteristics are investigated, and "portfolio maps" are provided as guides to help system designers identify appropriate portfolio characteristics when operating in a calendar-based design environment (which is the paradigm shift that space responsiveness introduces).

Nomenclature

TD_i	=	Time-to-Delivery for each instrument, months
$TD_{s/c}$	=	Time-to-Delivery of the spacecraft, months
m	=	mean of a lognormal distribution
v	=	variance of a lognormal distribution
μ	=	mean of a normal distribution
σ	=	standard deviation of a normal distribution
$\boldsymbol{Pf}$	=	spacecraft portfolio vector
n	=	portfolio size or number of instruments in the spacecraft portfolio
T_{int}	=	duration of the Integration & Testing phase, months
a	=	slope of the linear model of the average T_{int}
b	=	intercept parameter of the linear model of the average T_{int}
T_{ship}	=	duration of the shipping phase, months
TRL_{ini}	=	initial TRL of instruments in the portfolio
mr	=	schedule risk level or schedule margin, years
SR_{mr}	=	schedule risk for risk level mr
δ	=	degree of TRL-heterogeneity
μ_{TRL}	=	average TRL of the instruments in the portfolio
$\hat{\mathbf{u}}_{\mathbf{s/c}}$	=	instantaneous utility vector of the spacecraft
$\hat{u}_i$	=	utility per unit time provided by instrument i

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$\hat{u}_{tot}$	=	total utility per unit time provide by the spacecraft (scalar)
τ_{ops}	=	time horizon of interest, months
u	=	cumulative utility provided by the spacecraft after the time horizon of interest
$H(.)$	=	Heaviside step function

I. Introduction

Schedule slippages continue to plague the space industry as reflected by the months and sometimes years of delay experienced by several space programs. In particular, the Department of Defense (DOD) has repeatedly struggled to keep the development of its new space capabilities on schedule. As illustrated in Figure 1, several major DOD programs, such as the Advanced Extremely High Frequency satellites (AEHF), or the Wideband Global SATCOM (WGS) have suffered from delays equal or greater than 2 years; in the case of the Space Based Infrared System High (SBIRS-High), launch schedule slipped by as much as six years. Details about these programs are available in the corresponding reports published by the Government Accountability Office (GAO).[1,2]

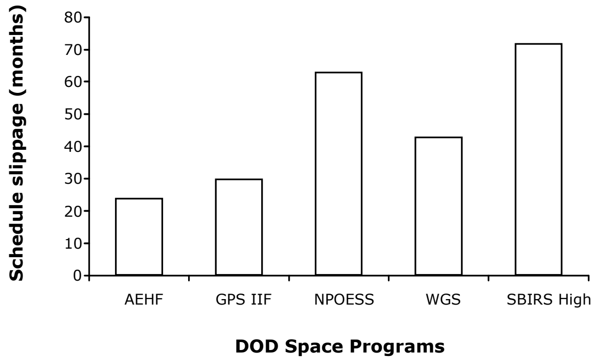

Figure 1. Delays and schedule slippage since program start as of April 2007 (adapted from GAO-07-730T[2])

Similarly, "GAO and others have reported that NASA has experienced […] schedule growth in several of its projects over the past decade".[3] Figure 2 represents the schedule growth for 18 NASA missions launched since the late 1990's (between the estimated launch date at the Preliminary Design Review and the actual launch date). Most missions experienced schedule slippage, and eight of them had a delay of more than a year.

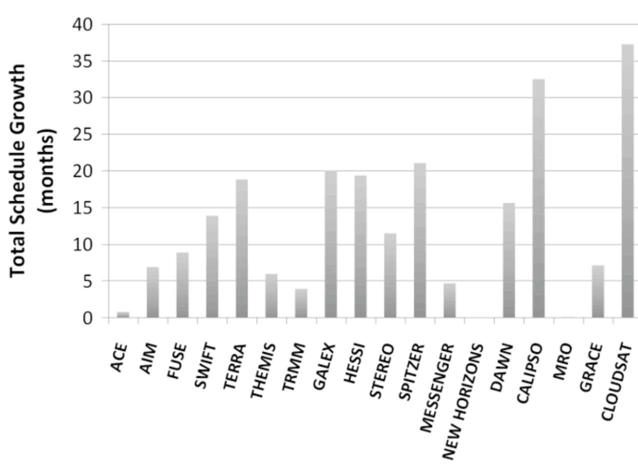

Figure 2. Schedule growth for various recent NASA missions

The repeated pattern of these schedule slippages suggests fundamental flaws in managing spacecraft delivery and schedule risk, and a limited understanding of the drivers of schedule slippages. The attention given to the delivery schedules of space systems however extends beyond the sole issue of avoiding slippages. Indeed, the importance of faster development and launch of space systems is increasingly acknowledged in the military and commercial sectors. Necessary efforts regarding the delivery schedules of space programs are required from the space industry not only to limit the extent and likelihood of slippages, but also to compress these schedules in order to make the space industry's value-chain more responsive to new or evolving customers' needs. In response to this critical issue, the Government Accountability Office has issued numerous reports providing recommendations to the DOD and NASA to limit schedule slippage in space programs. Their suggestions range from adopting better practices in the acquisition process to making appropriate design-related decisions that have an impact on schedule. Specifically, the GAO argued that the less mature the technologies are in an acquisition program, the more likely the program will experience (greater) schedule slippage[4]. In Dubos et al.[5], the authors conducted a statistical analysis of spacecraft schedule risk and slippage as a function of the average Technology Readiness Level (TRL) of the system. They provided a probabilistic assessment of the likelihood and extent of schedule slippage as a function of the spacecraft technology maturity. The results confirmed and quantified GAO's findings regarding the correlation between low TRL and increased schedule risk. The sole consideration of technology maturity however is not sufficient to explain the extent and variability of schedule slippage. Further research is thus needed to better characterize the joint effect of technology maturity and other potential sources of variability in schedule.

In this work, we extend in two directions the univariate analysis of schedule slippage in Ref. 5. It is useful to recall that the concept of technology maturity has its primary meaning when considered at the subsystem or single-instrument level. In Dubos et al.[5], the models developed to characterize the variability of schedule as a function of the spacecraft technology maturity used an average or aggregate TRL of the spacecraft subsystems. The analysis provided a preliminary understanding of the impact of technology maturity on schedule. In this work, we first extend the analysis in Ref. 5 by increasing the resolution on the technology maturity and assigning a TRL to each of the subsystems or instruments considered for the spacecraft. Second, various design parameters, other than TRL, can drive schedule and also be considered as "levers of responsiveness".[6] For example, the size and/or complexity of a spacecraft, defined by its number of subsystems or instruments, is likely to affect the final delivery schedule of the spacecraft. The idea that, with a large number of instruments, the completion of an entire spacecraft is more likely to be delayed due to slippage in the development of one immature instrument is supported by historical evidence. For example, the GAO reports[7] that in the case of the DOD's Space-Based Infrared System (SBIRS), "several design modifications have been necessary, including 39 modifications to the first of two infrared sensors to reduce excessive noise created by electromagnetic interference—a threat to the host satellite's functionality—delaying delivery of the sensor by 10 months" […] Moreover, delays in the development of the first sensor have had a cascading effect. […] Program officials […] agreed that these delays put the remaining SBIRS High schedule at risk." To quantitatively characterize this risk, we thus propose in this paper to add a portfolio dimension to our analysis of spacecraft schedule by considering the impact of the number of instruments, their individual technology maturity and the resulting TRL heterogeneity on the Time-to-Delivery of the entire spacecraft.

In the literature on and practice of Research & Development (R&D) management, a similar problem has been tackled, and the general approach for handling this problem is commonly referred to as "portfolio management" (with the qualifiers "R&D" or "technology" often preceding it). In this paper, we adapt the idea of technology portfolio from the macro- or company level to the micro-level of a single complex engineering system and investigate its relevance and implications. More specifically, we consider a spacecraft as a portfolio of technologies and instruments. This portfolio is (to be) embedded *within* the spacecraft and is characterized by the triplet (number of instruments –or size–, individual TRLs, TRL heterogeneity). This technology portfolio characterization endogenous to the system can be considered as one proxy for the spacecraft's complexity.

The remainder of this paper is organized as follows. In Section II, we provide a brief overview of the concept of portfolio as it has traditionally been implemented by successful companies and show the relevance of this approach to spacecraft design and schedule analysis. In Section III, we model the relationship between technology maturity and delivery schedule at a micro-level by formulating a probabilistic model of the Time-to-Delivery (TD_i) for each instrument of the spacecraft's "portfolio." Based on actual data, we then develop models for the Time-to-Integration of the spacecraft as a function of the number of instruments and for the Shipping time of the spacecraft. We finally simulate the development of the entire spacecraft by running Monte Carlo simulations of the three models sequentially: the concurrent development model of each instrument of the spacecraft portfolio, the model of Time-to-Integration of the whole spacecraft, and the model of Shipping time. The result is an important new random variable, referred to in this work as the spacecraft Time-to-Delivery ($TD_{s/c}$), and defined as the time elapsed from the start of the program until the spacecraft is launched. This new random variable (along with its mean and dispersion) is one important characterization of responsiveness and is dependent on both the "size" and the maturity of the spacecraft's technology portfolio. From the distribution of $TD_{s/c}$, we then formulate the notions of Mean-Time-To-Delivery (*MTTD*) of a spacecraft and its schedule delivery risk. In Section IV, we investigate how the *MTTD* and schedule delivery risk are affected by the choice of the spacecraft technology portfolio (i.e., by varying the "size" of the portfolio and the individual technology maturities). Homogeneous TRL cases (with only instruments of identical initial TRL) and heterogeneous ones are considered. Finally, we investigate in Section V the utility implications of varying the portfolio characteristics and time-horizons, and provide "portfolio maps" as guides to help system designers identify appropriate portfolio characteristics when operating in a calendar-based design environment (which is the paradigm shift that space responsiveness introduces, as we argue in Section V).

II. Spacecraft as a Technology Portfolio

A. The concept of portfolio in Finances and Research & Development

In the 1950's, Markowitz formulated the basic concepts of the Modern Portfolio Theory for financial assets, which rapidly generated significant interest in academia and in the financial industry. According to Markowitz' rule of mean-variance of returns, an investor should choose the portfolios of assets that maximize the expected value of return for a given variance of return (i.e., the "financial risk") or minimize the variance of return for a given expected value of return.[8] This principle highlighted the importance of the diversification of assets in order to optimize the value of the entire portfolio. In the field of Research & Development (R&D), this problematic found much resonance within companies having to decide on the types of research projects to support and the appropriate amount of resources to allocate to new projects. Since the 1970's, the idea of R&D portfolios has gained strong foothold in industry and academia, and numerous studies tackling the issue of technology portfolio management have been conducted and published, sometimes under the heading of "New Product Development" (NPD).[9,10] The similarities between R&D portfolio and the initial Markowitz formulation involving financial assets have been summarized by Roussel et al.: "the purpose of both business and R&D portfolio planning typically is to reach the optimum point between risk and reward, stability and growth".[11] More recently, Cooper et al. proposed a formal definition of portfolio management:[12]

> "Portfolio management is a dynamic decision process, whereby a business's list of active new product (and R&D) projects is constantly updated and revised. In this process, new projects are evaluated, selected, and prioritized; existing projects may be accelerated, killed, or de-prioritized; and resources are allocated and reallocated to the active projects."

These definitions highlight several key notions characterizing the concept of portfolio and portfolio management. Five such key notions are discussed next:

1. Portfolio management is a **resource allocation** problem. It is the scarcity of resources (for example, funding or time) available to a company, which calls for the use of a framework to select and appropriately distribute the resources among the promising projects. In fact, resource limitations that were overlooked during the selection process often explain project cancellation.[13,14]

2. In portfolio management, **innovation** is recognized as essential to the sustainable success of a company. The constitution of a portfolio is thus directly related to the amount of innovation in which a company is willing to invest in order to meet its objectives. Innovating projects may offer novel capabilities or enhanced performance benefits over existing offerings (products or services) and can potentially give a company a competitive advantage by positioning it as a leader in an emerging market.[9] On the other hand, such projects often require, in the short-term, significant resource investments while offering the possibility of mid- or long-term returns on those investments.

3. As suggested by Markowitz[8] and Roussel et al.[11] **uncertainties and risk** are essential motivations for the portfolio mindset, whether in finance or in technology R&D. In a 2007 report, the GAO advocated the use of a portfolio management approach for the DOD acquisitions by noting that focusing excessively on new products in isolation could "result in long cycle times, wasted money and lost opportunities elsewhere".[15] In addition to the technical risks and performance uncertainties inherent to new and unproven products/projects, environmental uncertainties (e.g., related to the dynamics of the market) put the portfolio selection process in a stochastic (dynamic and non-deterministic) context.

4. In presence of limited resources and various sources of uncertainties, the **balance** of the resources allocation among projects is therefore a key notion to ensure that these resources are used in an optimal way, that is, to both maximize the return on investment and mitigate risk through diversification. In summary, portfolio management is about the "**optimal investment mix** between risk versus return, maintenance versus growth, and short-term versus long-term new product projects".[16]

5. Finally, project selection for the constitution of a portfolio is a **dynamic, iterative process**, in which "[decisions] are revisited at multiple stages throughout product development in a gated review and assessment process".[15]

Numerous methods have been proposed and extensively discussed in the literature on developing and managing an R&D portfolio. Archer and Ghasemzadeh[13] distinguished these methods by identifying the following three major phases in the process of constituting an R&D portfolio: strategic considerations, individual project evaluation, and portfolio selection.

In the first phase, a company identifies market opportunities and formulates a strategy to tackle these opportunities. From a customer perspective, strategies to position the company on the market can be for example operational excellence, product leadership or customer intimacy.[17] A set of objectives is then defined to support this strategy. Ultimately, portfolio management aims at aligning the products or projects with these objectives.

In the second phase, projects are evaluated individually on the objectives listed by the company. Such criteria are for example expected profits, time-to-completion, cost, probability of success, etc.[11] Very often, criteria can be conflicting (e.g., reducing the time-to-completion could reduce the probability of success). A myriad of methods, quantitative and qualitative, have been proposed to perform this multi-criteria evaluation task. Thorough reviews of the literature on these techniques have been provided by Baker and Freeland,[18] Cooper et al.,[12] Chen-Fu Chien,[19] Linton et al.,[20] Henriksen and Traynor,[21] Martino.[22] From a quantitative perspective, financial models based on net present value (NPV),[23,24] and Real Options Theory[25,26,27] have been proposed. While these techniques are formal and quantitative, some business managers find them somewhat impractical and conveying a flawed sense of precision (when the numbers can be easily manipulated to support any decision). As a result, more qualitative methods such as checklists or scorecards, with various figures of merit for each project, have thus sometimes been used instead.[28]

In the third phase, once the projects have been evaluated individually, the "portfolio" is constituted by comparing projects with each other and selecting appropriate combinations in line with the company's strategy and resources. Qualitative methods such as the Analytic Hierarchy Procedure (AHP)[29,30] or the 2D bubble diagrams[11] have gained much popularity in corporate settings due to their accessibility. Several mathematical approaches are also available to select the best combinations by maximizing an objective function using for example linear programming.[31] Multi-attribute value/utility (MAV/MAU) methods have also been employed to obtain the overall value of a portfolio after computing the technical worth of individual projects.[32]

It is important to note that "the combination of individually good projects [does not] necessarily constitute the optimal portfolio",[19] and that the emergent properties of the portfolio are more than the sum of properties of each individual project. Thus, a critical issue in portfolio management concerns the aggregation of attributes of each project into the final portfolio.

B. Spacecraft as a technology portfolio

In this paper, we propose the idea that system design is, in several ways, a process similar to the constitution of an R&D portfolio. We conceive of a spacecraft as a "technology portfolio" or a portfolio of technologies. We focus on the characteristics of this portfolio, the system's size (e.g., number of instruments), the technology maturity of each instrument, and the resulting TRL heterogeneity of the portfolio, and investigate their effects on the delivery schedule of a space system, its schedule risk, and its utility over varying time-horizons.

By conceiving of an engineering system as a value-delivery artifact,[33] we encounter a fundamental systems engineering and design principle similar to the one in portfolio selection, that "the whole is greater than the sum of its parts". Furthermore, beyond the housekeeping subsystems of a spacecraft (e.g., power, attitude control, Telemetry, Tracking, and Command), we focus in this work on the value-delivering elements of a spacecraft, hereafter referred to as the "instruments" or payload, as the constitutive elements of the spacecraft "technology portfolio". Our definition of "instrument" as a value-delivering part of a spacecraft is intentionally extensible. For example, in the case of a technology demonstration mission, the "instrument" is the subsystem being tested (such as the attitude determination device "Compass" carried onboard the Space Technology 6 (ST6) spacecraft for NASA's New Millennium Program).

Using a portfolio approach, the selection of these instruments is performed in order to balance return on investment (such as science return) and risk (e.g., schedule risk or cost risk). As discussed previously, this selection is a dynamic, stage-gated process during which decisions are revisited, as more knowledge of the instruments, the customer requirements, and the constraints becomes available. In Figure 3, we show a typical "funnel representation" of portfolio selection to illustrate this design process.

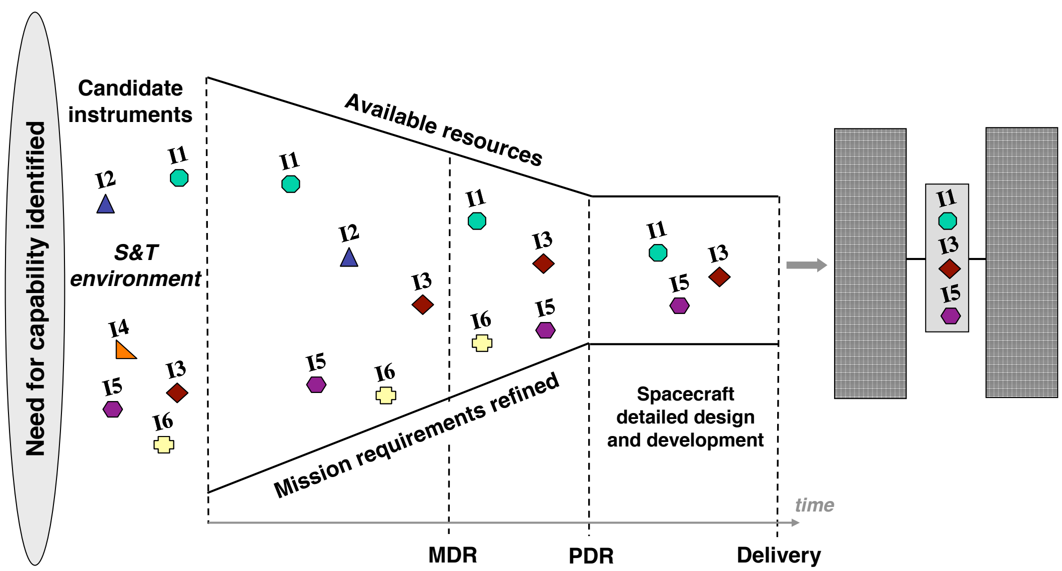

Figure 3. Funnel representation of a spacecraft as a "portfolio of instruments" (Adapted from GAO [15])

Figure 1 is a digraph flowing from left to right, and it reads as follows. To the left, a customer need or market opportunity is identified for which a set of spacecraft capabilities is required to address or capture (in whole or in part). To provide these capabilities, various candidate instruments are considered (e.g., candidates I1 to I6 at the onset of the "funnel"). If new capabilities are required, the technologies characterizing the candidate instruments may have low maturity levels and still be under development in a Science & Technology (S&T) environment.[4] As a result, some candidate instruments, because of their low technology maturity, may not make it past the first gate or filter in the funnel (e.g., instrument I4 in Fig. 1). As the mission requirements and constraints are refined (moving to the right in Fig. 1), available resources are concentrated on the instruments that can best meet the objectives. The number of candidate instruments thus decreases as these pass the different gates or reviews (such as the Mission

Definition Review). After the Preliminary Design Review (which traditionally marks the end of Phase B), a "design-to" baseline is usually chosen and further modifications to this baseline should only represent refinement and not fundamental changes.[34] At this point, the down-selection of instruments is assumed to be complete. The detailed design and development of the spacecraft is then conducted (Phase C and Phase D) and end with the delivery of the spacecraft (launch).

C. Focus of the work

Among the several issues that should be examined during the constitution of a portfolio, three essential questions have to be addressed: 1) how many projects can the resources support (and how should they be allocated among the various projects), 2) how "innovative" these projects (or each project) should be, and 3) what are the implications (benefits and risks) associated with different portfolio choices. The "innovativeness" dimension of a project is often difficult to quantify. To circumvent this difficulty, in some corporate R&D settings, this innovativeness is replaced by the time-to-impact of the considered project, with H-1 characterizing projects that can bear fruits within one to three years, H-2 within three to five years, and H-3 past five years. In this work, we consider a spacecraft as a portfolio of technologies with a similar mindset; we therefore focus on 1) the number of instruments for a spacecraft (i.e., the portfolio size), 2) the initial technology maturity of each instrument (or its TRL, taken here as a proxy for innovativeness) in the portfolio and the resulting TRL heterogeneity of the portfolio. We then analyze the impact of these portfolio characteristics on the schedule delivery of the spacecraft and its schedule risk. Finally, we investigate the utility implications of varying the portfolio characteristics and time-horizons, and provide "portfolio maps" as guides to help system designers identify appropriate portfolio characteristics when operating in a calendar-based design environment.

III. Probabilistic Model of Spacecraft Time-to-Delivery

In this section, we formulate a probabilistic model of the Time-to-Delivery of a spacecraft, $TD_{s/c}$, based on the idea of technology portfolio. The novel random variable here introduced, $TD_{s/c}$, which in our calculations includes the time to delivery of all the spacecraft instruments, the time for Integration and Testing of the whole system, and the shipping time of the spacecraft to the launch range, is an essential measure for the quantification of space responsiveness and schedule risk. Quantitative measures are important in any effort to benchmark and improve a given situation, especially the critical issue of acquisition of weapon systems in general, and space systems in particular. $TD_{s/c}$ is one contribution in this direction.

A. Model of Instruments Delivery Schedule

The first component of $TD_{s/c}$ is a probabilistic model of Instruments Delivery Schedule, which relates the time needed to complete the development of all the instruments of the spacecraft to their initial technology maturities. The Instrument Delivery Schedule is also affected by the size of the spacecraft portfolio (i.e., its number of instruments) in a manner that is discussed next.

1. Distributions of Time-to-Delivery of Instruments

The main inputs of the Instruments Delivery Schedule model are the probability distribution functions of each instrument's Time-to-Delivery. Each instrument i of the spacecraft portfolio is characterized by an initial Technology Readiness Level TRL_i, and a probability distribution function describing the random variable Time-to-Delivery (TD_i) of this instrument. TD_i represents the time needed to fully develop an instrument and have it ready for integration in the whole spacecraft. This development of each instrument is subject to schedule uncertainty, which justifies the use of a probability distribution to model the Time-to-Delivery. In the following, we use lognormal distributions, which are by definition probability distributions of a random variable whose logarithm follows a normal distribution. The mean m and the variance v of the lognormal distribution can be related to the mean μ and standard deviation σ of the associated normal distribution via Eq. (1):

$$\begin{cases} \mu = \ln\left(\dfrac{m^2}{\sqrt{v+m^2}}\right) \\ \sigma = \sqrt{\ln\left(\dfrac{v}{m^2}+1\right)} \end{cases} \quad \textbf{(1)}$$

As a result, for a given initial TRL_i, and a mean m_i and a variance v_i for the random variable TD_i (or, equivalently, a mean μ_i and a standard deviation σ_i for the random variable $ln(TD_i)$), the Time-to-Delivery follows the distribution expressed in Eq. (2) (justification for the use of the lognormal distribution is provided in the Appendix):

$$f(TD_i, m_i, v_i) = \frac{1}{TD_i \sigma_i \sqrt{2\pi}} e^{-\frac{(\ln(TD_i)-\mu_i)^2}{2\sigma_i^2}} \quad \textbf{(2)}$$

One distribution of Instrument Time-to-Delivery corresponds to one value of the initial TRL of the instrument considered. The use of more mature technologies compresses schedule and reduces schedule uncertainty, resulting in a decrease of both the mean and the variance of the distributions of Time-to-Delivery, as shown in Figure 4.

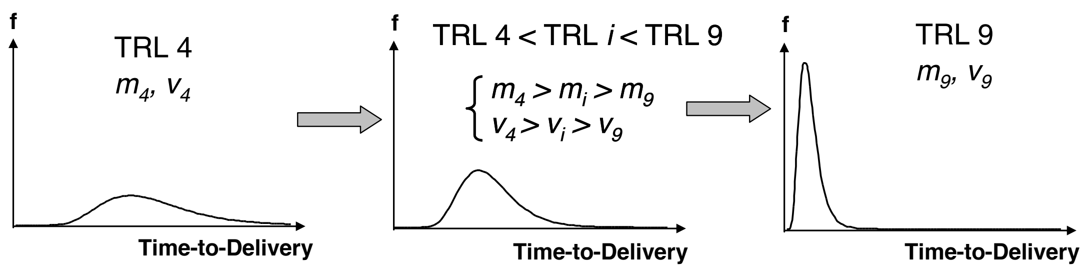

Figure 4. Distributions of Instrument Time-to-Delivery for various values of the initial TRL of the instrument

Only values of the initial TRL ranging from 4 to 9 are considered in this work, since TRL 1 through TRL 3 usually correspond to the early research and feasibility study stages rather than the technology development phase. Additional details regarding the TRL scale can be found in Ref. 35.

2. *Portfolio vector*

The composition of the spacecraft is now described via a technology "portfolio vector" ***Pf***, whose elements are the values of the initial TRL for each instrument *i*. As the size of this portfolio vector represents the actual number of main instruments of the spacecraft, several TRL values may be repeated in the vector if the development starts at the same initial TRL for different instruments.

$$\boldsymbol{Pf} = \begin{bmatrix} TRL_1 & TRL_2 & \ldots & TRL_n \end{bmatrix} \quad \textbf{(3)}$$

For example, a spacecraft whose technology portfolio is ***Pf*** = [6 6 8 9] contains 4 instruments, two with an initial TRL of 6, one that has been completed and qualified through test and demonstration (TRL 8), and one that has been qualified through successful mission operations (TRL 9). In the following, *n* is used to refer to the size of the Technology Portfolio, i.e., the number of instruments.

3. *Instruments Delivery Schedule*

The development of the instruments is illustrated in Figure 5, and is carried out in a non-sequential manner, either concurrently or with varying time overlap.

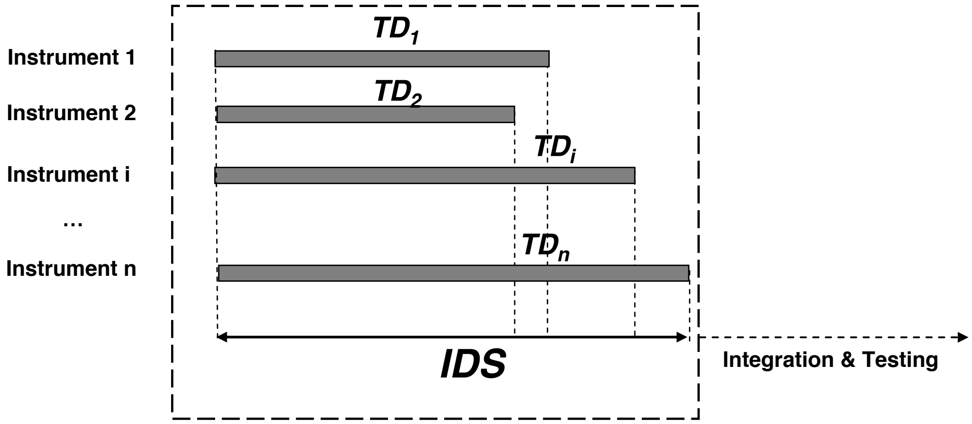

Figure 5. Instruments Delivery Schedule of a spacecraft (illustrative)

The subsequent step towards the completion of the spacecraft is the Integration and Testing phase, which starts when all the instruments have been developed and are "readied", or stated differently, when the development of the last instrument has been completed. (Analysis of master schedules of several historical NASA missions revealed that the development of the spacecraft bus – which will host the instruments – usually ends before or coincides with the completion of the last instrument. For this reason, completion of the last instrument has been chosen as the stopping condition for the Instrument Delivery Schedule). Assuming that the development of all the spacecraft instruments is triggered around the same time (given that is the call for and contracting of all the instruments is usually issued around the same time), we thus define the Instruments Delivery Schedule (*IDS*) as the maximum Time-to-Delivery (TD_i) of all the instruments in the spacecraft's portfolio vector. The analytic expression of IDS is shown in Eq. (4):

$$IDS = \max_{i \in Pf} \left(TD_i \right) \tag{4}$$

As each instrument's Time-to-Delivery (TD_i) is a random variable, the resulting *IDS* is also a random variable (nonparametric, unlike the parametric lognormal distribution of TD_i).

B. Model of spacecraft Integration & Testing

Once all the instruments have been developed, they have to be integrated into the spacecraft and tested before the whole system is readied and delivered to the launch range. Therefore, in addition to the *IDS*, our model of Time-to-Delivery for an entire spacecraft includes a second model accounting for the Integration & Testing (I&T) phase of the instruments. The second "dimension" of the portfolio, namely its size (or number of instruments) is expected to directly influence the duration of this phase. In the following, we refer to T_{int} as the duration of spacecraft Integration & Testing. To analyze the impact of the portfolio size on T_{int}, we considered schedule data from 21 NASA spacecraft for which the duration of the I&T phase as well as the number of instruments were available. In this sample, the number of instruments per spacecraft ranged from one to six. Within each of these six categories, we computed the average duration of Integration & Testing, as shown on Figure 6 as a function of the number of instruments.

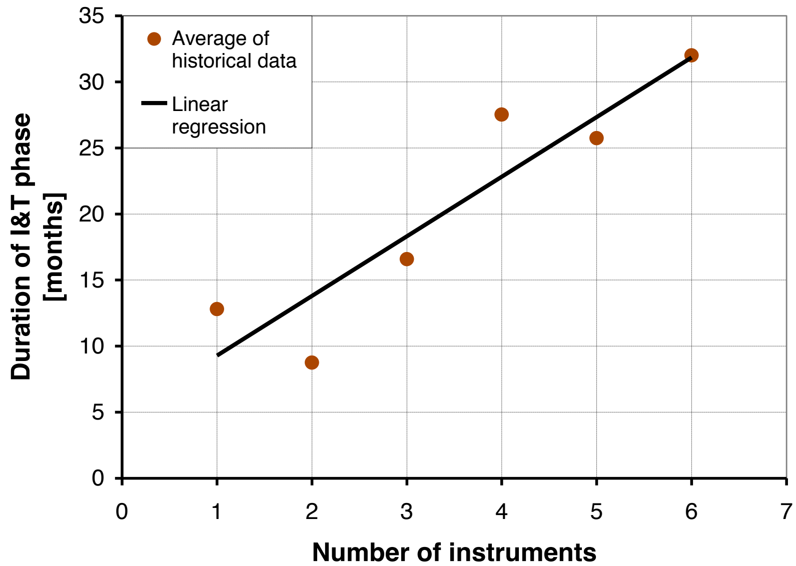

Figure 6. Model of average duration of Integration & Testing as a function of the number of instruments

The visible trend in Figure 6 confirms the intuition that on the average, the I&T phase of a spacecraft with many instruments (i.e., a "large portfolio size") takes longer than that of a spacecraft with fewer instruments. Stated differently, the more instruments a spacecraft has, the longer the average T_{int}. Consider now a linear model of the average T_{int}, as expressed in Eq. (5):

$$\langle T_{int} \rangle = a \cdot n + b \qquad \textbf{(5)}$$

n represents the number of instruments in the spacecraft, and a and b are the parameters of the regression line. The resulting coefficient of determination is $R^2 = 0.8448$, which along the visual inspection of Figure 6 indicate that a linear regression of this data provides a reasonable model to capture the average duration of the I&T phase for varying number of instruments. The parameters of this linear model [Eq. (5)] are provided in Table 1.

Table 1 Model parameters for the average T_{int} in the data set

Model Parameter	Value
a	4.5109
b (month)	4.7759

This model however does not capture variability or schedule uncertainty in the I&T phase. To do so, we consider T_{int} as a random variable instead of the single average value provided by Eq. (5), and we use lognormal probability distribution functions to model T_{int} (the justification of this choice is provided in the appendix). Furthermore, for each value of the portfolio size, the mean m_n of the corresponding lognormal distribution is given by Eq. (5), namely $m_n = \langle T_{int} \rangle$. The standard deviation is independent of the portfolio size, and is calculated based on actual data from the 21 NASA spacecraft considered.

The resulting model for T_{int} is given by Eqs (6) and (7):

For a given portfolio size n,

$$f(T_{int}, m_n, v) = \frac{1}{T_{int}\sigma_n\sqrt{2\pi}} e^{-\frac{(\ln(T_{int})-\mu_n)^2}{2\sigma_n^2}} \qquad \textbf{(6)}$$

$$\text{with}\quad \begin{cases} \mu_n = \ln\left(\dfrac{m_n^2}{\sqrt{v+m_n^2}}\right) \\ \sigma_n = \sqrt{\ln\left(\dfrac{v}{m_n^2}+1\right)} \end{cases} \qquad \text{and} \qquad \begin{cases} m_n = a\cdot n + b \\ v = \text{constant} \end{cases} \tag{7}$$

C. Model of Spacecraft Shipping Time

Once all the instruments have been delivered, and the spacecraft has been integrated and tested, it is ready to be shipped to the launch site. A few months are typically needed to ship the spacecraft to the launch site and integrate it to the launch vehicle, before it is delivered on-orbit to the customer and starts providing service. A brief holding time may also be needed before the launch range and/or the launch vehicle is ready. For the purpose of our study, we derived a probabilistic model of the duration of this phase (that we refer to as "Shipping time" in a broad sense), based on the data from the 21 NASA spacecraft in our database. Figure 7 shows the distribution of spacecraft shipping time in the sample, along with a lognormal fit of the data (the justification of the lognormal distribution for T_{ship} is discussed in the appendix).

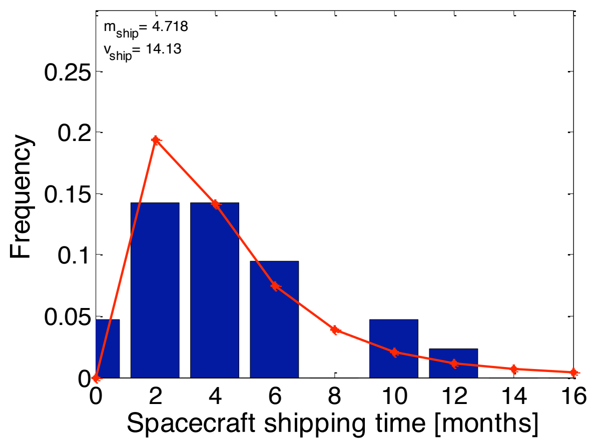

Figure 7. Distribution of the spacecraft shipping time in the data sample and associated lognormal fit

The probability distribution function of the spacecraft shipping time T_{ship} is given in Eq. (8):

$$f(T_{ship}, m_{ship}, v_{ship}) = \frac{1}{T_{ship}\sigma_{ship}^2\sqrt{2\pi}} e^{-\frac{(\ln(T_{ship})-\mu_{ship})^2}{2\sigma_{ship}^2}} \tag{8}$$

$$\text{with}\quad \begin{cases} \mu_{ship} = \ln\left(\dfrac{m_{ship}^2}{\sqrt{v_{ship}+m_{ship}^2}}\right) \\ \sigma_{ship} = \sqrt{\ln\left(\dfrac{v_{ship}}{m_{ship}^2}+1\right)} \end{cases}$$

m_{ship} and v_{ship} are respectively the mean and variance of the distribution. The values of these parameters resulting from the lognormal fit of the data are provided in Table 2.

Table 2 Parameters of the lognormal model for the spacecraft shipping time T_{ship}

Model Parameter	Value
m_{ship}	4.7178
v_{ship}	14.1339

D. Monte-Carlo simulations

We now have three random variables that contribute to the Time-to-Delivery $TD_{s/c}$ of a spacecraft. The three variables are the Instruments Delivery Schedule, *IDS*, the duration of spacecraft Integration & Testing phase, T_{int}, and the shipping time T_{ship}. Furthermore, the first random variable, *IDS*, results from a mathematical operation [Eq. (4)] on multiple random variables, namely the Time-to-Delivery (TD_i) of all the instruments. As a result, in order to propagate the uncertainties on the input (random) variables, and capture their effect on the output of interest, namely the spacecraft Time-to-Delivery $TD_{s/c}$ [Eq. (9)], we need a numerical simulation method that can reproduce the random nature of the inputs. This is typically done using a Monte-Carlo simulation, which is obtained by running an analytical model with random variables a large number of times (typically several thousands of run) and picking different values from the probability distribution functions of the input variables at each run.[36]

The probability density functions of the three input random variables (TD_i, T_{int}, T_{ship}) are given in Eqs (1), (6), and (8). As an illustration of Monte Carlo simulation, we used these equations to randomly generate 50,000 values for each of these random variables. The intermediate results are shown in Figure 8, Figure 9, and Figure 10. In the next subsection (III–E), we use Monte Carlo simulations to derive the end result of interest in this work, namely the spacecraft Time-to-Delivery $TD_{s/c}$ for varying portfolio vectors, that is for different payload sizes, and different TRL's of its constitutive instruments (as discussed in Section II).

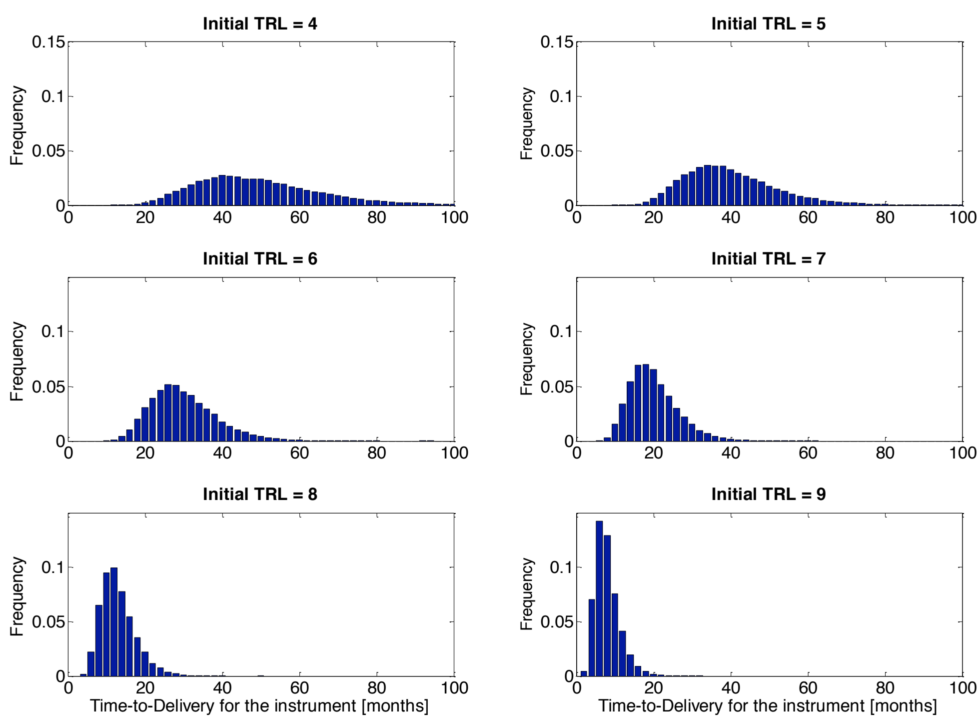

Figure 8. Lognormal distributions of the Time-to-Delivery for the instruments, for each value of the initial TRL

Based on the functional form of Eq. (2), Figure 8 represents the six lognormal distributions obtained after generating random values for the Time-to-Delivery of the instruments, given their initial TRL (from TRL_{ini} = 4 to TRL_{ini} = 9). Note that their form corresponds to the trends presented on Figure 4.

Similarly, Figure 9 represents the six lognormal distributions of Eq. (6) that model the duration of the spacecraft Integration & Testing for values of the portfolio size ranging from $n = 1$ to $n = 6$. Observe that while the dispersion of the random data generated by Monte-Carlo simulation shows little variation, the mean duration increases as the portfolio size increases, as described by Eq. (7).

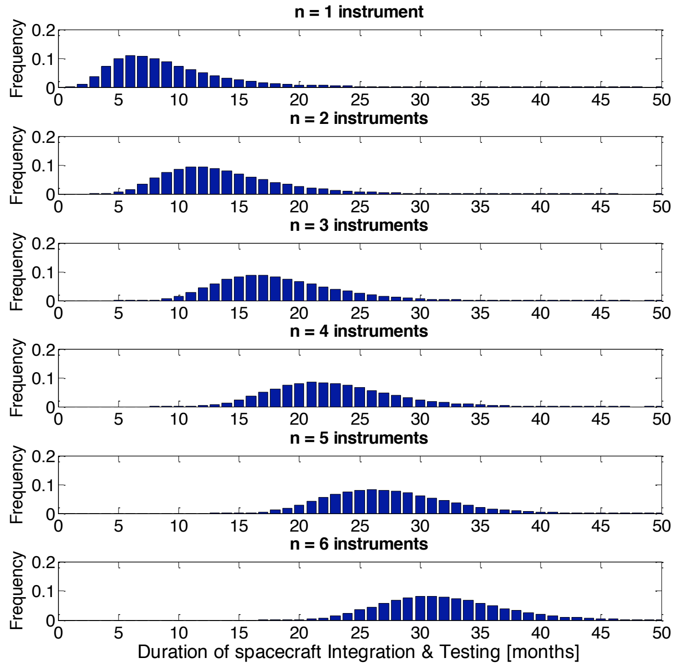

Figure 9. Lognormal distributions of the spacecraft Integration & Testing Time for each value of the portfolio size *n*

Finally, the random data generated for the duration of spacecraft shipping following the model of Eq. (8) is shown in Figure 10.

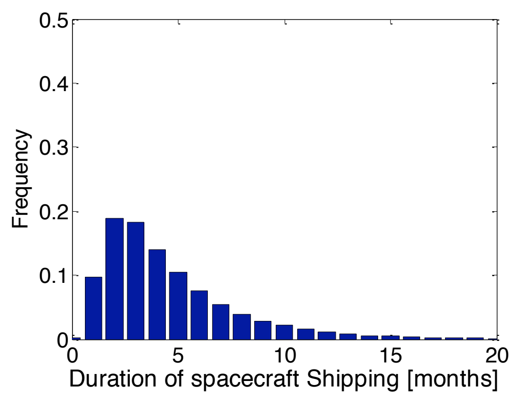

Figure 10. Lognormal distribution of the spacecraft Shipping Time

E. Final Model of Spacecraft Time-to-Delivery

The final model of spacecraft Time-to-Delivery $TD_{s/c}$ estimates the total time needed from the start of the development of the instruments to the instant when the spacecraft is launched. This final model therefore calculates the spacecraft Time-to-Delivery $TD_{s/c}$ by summing the durations of the three previous consecutive phases, the Instruments Development Schedule, the Integration & Testing, and the Shipping [Eq. (9)]:

$$TD_{s/c} = IDS + T_{int} + T_{ship} \tag{9}$$

Since IDS, T_{int}, and T_{ship} are random variables, the spacecraft Time-to-Delivery $TD_{s/c}$ is also a random variable with a probability density function numerically derived through the Monte Carlo simulation discussed previously. The process for calculating $TD_{s/c}$ *is* illustrated in Figure 11.

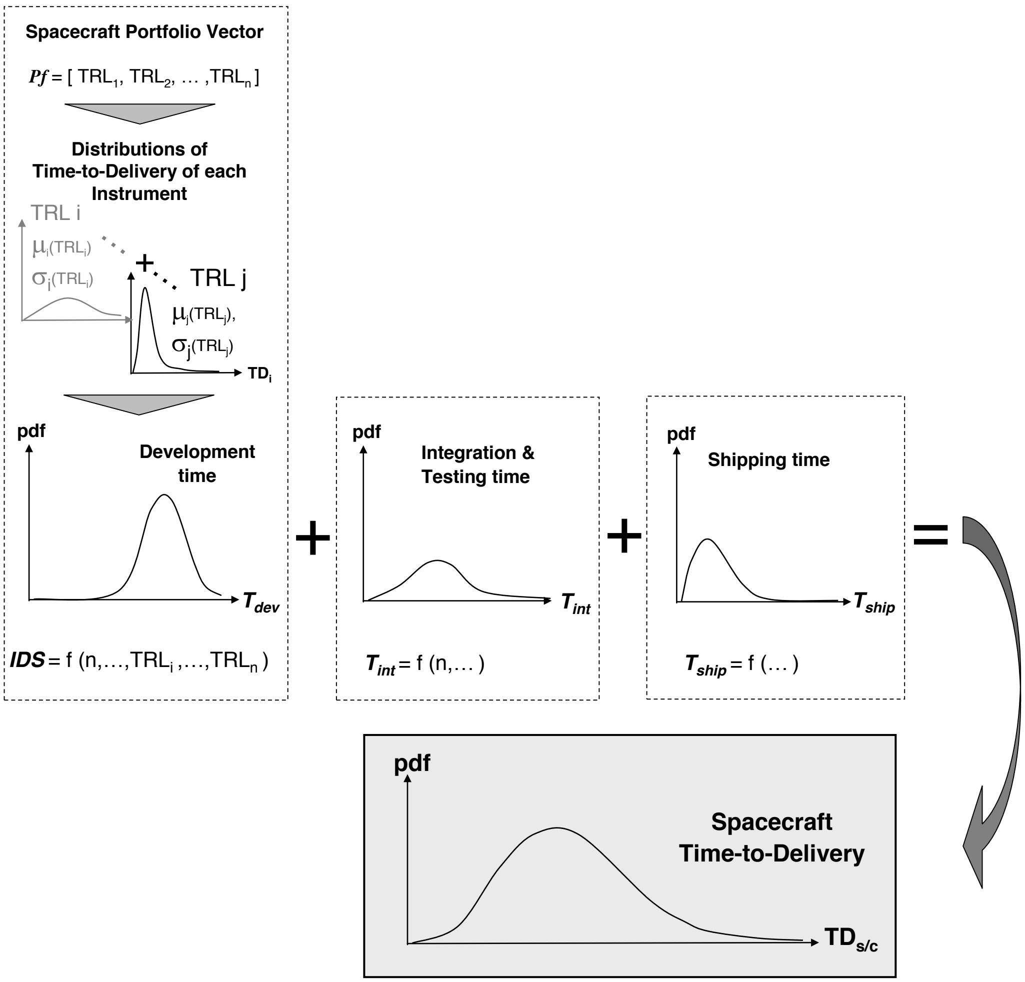

Figure 11. Summary of the model of spacecraft Time-to-Delivery

From the output probability distribution function of spacecraft Time-to-Delivery, $TD_{s/c}$, we define two important quantities:

1. The first measure is the mean of this output random variable $TD_{s/c}$, which we refer to hereafter as the **Mean-Time-To-Delivery** (*MTTD*) of the spacecraft. The concept of a *MTTD* of a spacecraft is one important quantitative metric for the analysis, measurement, and improvement of space responsiveness (see Ref. 6 for more details on the concept of space responsiveness).
2. Furthermore, we consider a measure of variability of the spacecraft Time-to-Delivery. Instead of using the standard deviation of the spacecraft Time-to-Delivery, we define a measure that should prove more useful to system engineers and program managers, namely the likelihood of overshooting a given schedule estimate, which represents a form of schedule risk. More specifically, we define a family of schedule risk SR_{mr}, for various value of mr, as discussed next. Considering that the *MTTD* for a spacecraft constitutes a reasonable estimate that program managers could follow in planning the schedule, we first define the Schedule Risk SR_0 as the probability that the spacecraft Time-to-Delivery exceeds the *MTTD*:

$$SR_0 = P\{TD_{s/c} > MTTD\} = \int_{MTTD}^{\infty} f(t)dt \qquad \textbf{(10)}$$

f is the probability density function of $TD_{s/c}$ as represented on Figure 11. When defining any type of risk, it is often useful to specify the "risk level" considered. Risk is indeed commonly represented by a likelihood of occurrence of an event associated with the impact of this event, i.e., the "risk level". (Risk is however sometimes mistakenly considered as the product of the probability of occurrence p with the consequence of the occurrence c. This definition is flawed and represents a misunderstanding of the concept of risk.[37] Risk is defined for various scenarios with likelihood of occurrence AND consequences, and not likelihood times consequence, $p*c$, a product which reduces the two-dimensional risk problem into a meaningless single dimension). The schedule risk SR_0 of Eq. (10) captures all the various schedule slippages that can occur, relatively to the *MTTD* estimate. It is however possible to define other risk levels by focusing on more "severe" schedule slippages relatively to the *MTTD*, as follows:

$$SR_{mr} = P\{TD_{s/c} > MTTD + mr\} = \int_{MTTD+mr}^{\infty} f(t)dt \qquad \textbf{(11)}$$

mr represents, in years, the amplitude of the schedule slippage (from a program management perspective, *mr* can also represent the schedule margin planned for the program). For example, we consider in this paper the probability of overshooting the *MTTD* by 6 months $SR_{0.5}$, as well as the probability of overshooting the *MTTD* by one year SR_1, etc.

Figure 12 provides a visual illustration of the MTTD and schedule risk SR_0 given the Monte Carlo simulation output of the probability distribution function of spacecraft Time-to-Delivery, $TD_{s/c}$.

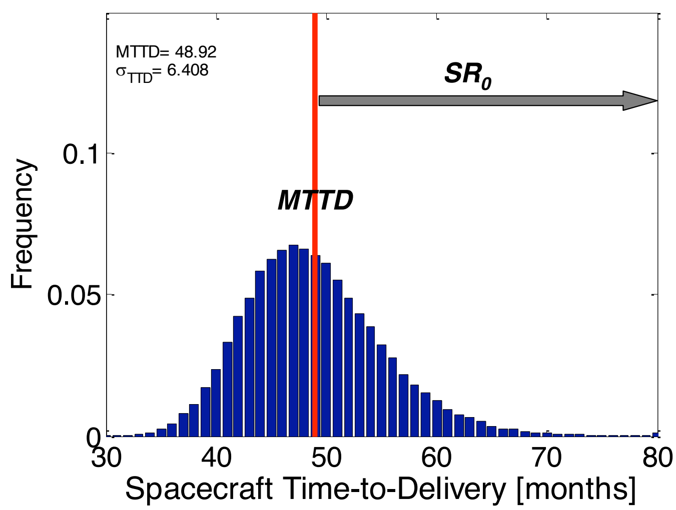

Figure 12. Final distribution of spacecraft Time-to-Delivery $TD_{s/c}$ with *MTTD* and SR_0

In the following section, we analyze the influence of the spacecraft portfolio choice on the *MTTD* and various Schedule Risks.

IV. Impact of Spacecraft Portfolio Choice on Mean-Time-To-Delivery and Schedule Risk

Farquhar and Rao[38] introduced the concept of "portfolio balance" by defining the total balance of a portfolio as "homogeneity or uniformity of scores of items on certain attributes" (equi-balance) and "heterogeneity and multiformity of scores of items" on others (counter-balance). In this section, we adopt a similar classification by defining the balance of a spacecraft technology portfolio with respect to the individual TRL of all its instruments. We investigate the impact of portfolio choice on *MTTD* and Schedule Risk, by distinguishing two types of "balance" of spacecraft portfolio: homogeneous TRL cases, and heterogeneous TRL cases.

A. Homogeneous TRL case

The portfolio configurations considered in this section are referred as "homogeneous" as each instrument constituting the portfolio is developed from the same initial TRL. Configurations for which the development of the instruments starts at various values of TRL for the different instruments (the heterogeneous TRL cases) are discussed in the next subsection.

1. *Analysis of Mean-Time-To-Delivery*

Figure 13a shows the influence of the initial technology maturity of the instruments, measured by the common value of their initial TRL, on the Mean-Time-To-Delivery of the spacecraft. Various portfolio sizes are represented, from $n = 1$ to $n = 6$ instruments. The two main ideas discussed in the Introduction can be found in Fig. 11a:

1. The *MTTD* of the spacecraft—recall this is the average of the random variable $TD_{s/c}$ whose probability distribution function is derived using Monte Carlo simulation and Eqs. 1 through 9—is reduced when the TRL of its instruments at the start of the spacecraft development is higher. In other words, a spacecraft on average will be completed and delivered faster when its instruments are more technologically mature. Indeed, a better knowledge of the technologies embodied in the instruments at the start of development compresses the delivery schedule of these instruments. For example, the output distribution of $TD_{s/c}$ obtained by the model shows that, for $n = 2$ instrument, the *MTTD* is reduced from roughly 78 months for $TRL_{ini} = 4$ to 30 months for $TRL_{ini} = 9$.

2. For any given value of the initial TRL of the instruments, the *MTTD* increases as the spacecraft portfolio size increases. In other words, a spacecraft on average will take longer to be completed and delivered when it has more instruments. This increase is caused by the effect of the number of instruments n on both the Instruments Development [Eq. (4)] and Integration & Testing [Eq. (5–7)] phases, as reflected by Eq. (9) and summarized in Figure 11.

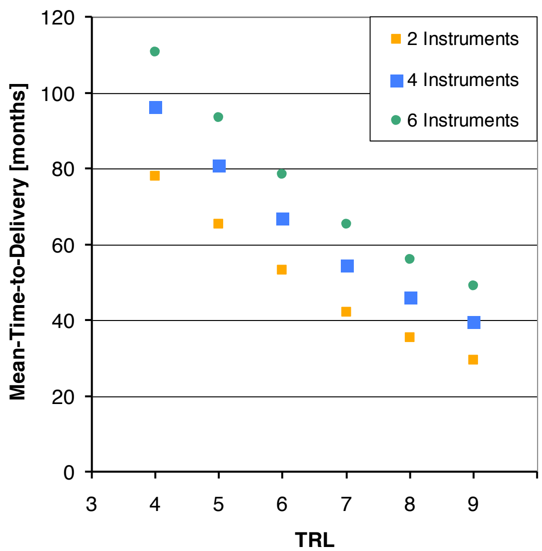

Figure 13a. *MTTD* as a function of the initial TRL of the instruments

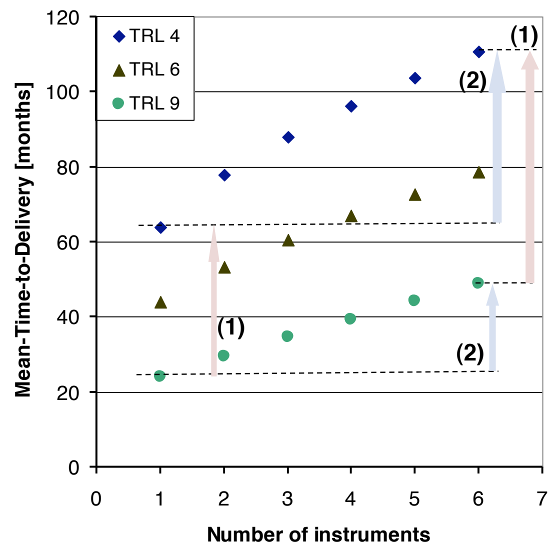

Figure 13b. *MTTD* as a function of the portfolio size

Figure 13b represents the same outputs of the model as those shown in Fig. 11a but from a different perspective that highlights the combined effect of portfolio size and technology maturity. More specifically, we see in Figure 13b:

1. The sensitivity of the *MTTD* to TRL increases when the number of instruments increases (see arrows labeled (1) in Fig. 11b). For example, when the spacecraft contains two instruments, its *MTTD* jumps from

30 to 78 months when the TRL of this instrument at the start of the spacecraft development drops from 9 to 4 ($\Delta MTTD$ of 48 months in the case of a two-instrument spacecraft). However, when the spacecraft contains 6 instruments, the *MTTD* jumps from 49 months to 111 months when the TRL drops from 9 to 4 ($\Delta MTTD$ of 62 months).

2. The impact of an increase in the number of instruments on the *MTTD* is more significant at low TRL (see arrows labeled (2) in Fig. 11b). For example, with one instrument at TRL = 9, the spacecraft's *MTTD* is 24 months and it increases to 49 months when the spacecraft contains 6 instruments. As a result, the $\Delta MTTD$ between one and six instruments at TRL = 9 is 25 months. However, when the spacecraft development starts with a single instrument at TRL = 4, its *MTTD* is 64 months and it increases to 111 months when the spacecraft contains of 6 instruments. The $\Delta MTTD$ in this case at TRL = 4 is 47 months.

These observations are two faces of the same coin and they characterize the joint effects of the spacecraft portfolio characteristic (size and technology maturity) on the Mean-Time-To-Delivery (*MTTD*) of the spacecraft. Incidentally, this finding provides one explanation to the larger dispersion of schedule slippages at low TRL than at high TRL, presented in [5].

2. Analysis of Schedule Risk

In addition to the *MTTD* results, we provide in Figure 14 the schedule risk curves as a function of the initial TRL of the spacecraft's instruments, for a portfolio of $n = 3$ instruments. A significant reduction of schedule risk is visible when the TRL of the instruments increases. Figure 14 reads as follows. For example, with instruments of TRL = 4 at the start of the spacecraft development, the spacecraft time to delivery has roughly a 25% likelihood of overshooting the *MTTD* estimate by one year ($mr = 1$ year). This probability drops to approximately 15% if the instruments' initial TRL is 6 (middle curve in Figure 14).

Furthermore, a vertical cut across Figure 14 reads as follows. For instruments with TRL = 6, there is a 3% likelihood of the spacecraft overshooting its *MTTD* by 2 years (in other words, it is quite unlikely). However, there is a 31% likelihood of the spacecraft overshooting its *MTTD* by 6 months.

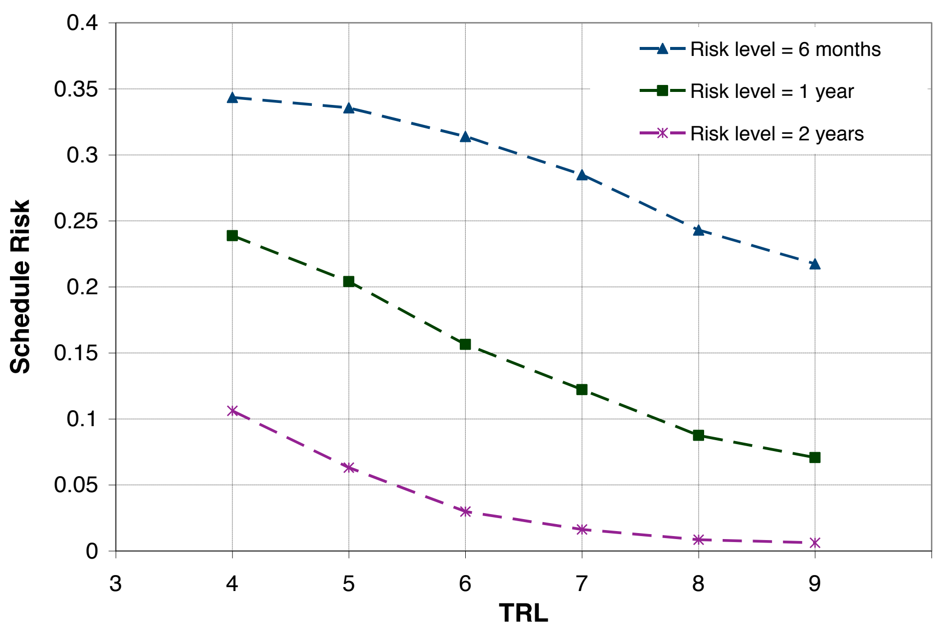

Figure 14. Schedule Risk curves as a function of the TRL of the instruments ($n = 3$), for various risk levels

The concept of schedule risk curves is particularly important in the design and acquisition of space systems. We recommend that the government and the space industry 1) adopt and develops, beyond the traditional single-point schedule estimate, schedule risk curves in space acquisition programs; 2) that these schedule risk curves be made available to policy- and decision-makers; and 3) that adequate schedule margins be defined according to an agreed upon acceptable schedule risk level.

B. Heterogeneous TRL case

The analysis in the previous subsection was confined to instruments of identical technology maturity at the start of the spacecraft development. The situation was referred to as the "homogeneous TRL case." In this subsection, we relax this constraint and investigate spacecraft portfolio with heterogeneous TRL instruments at the start of the spacecraft development.

A company may wish to allocate resources to different projects in its R&D portfolio that are not at the same stage of development or maturity. Similarly, instruments considered for inclusion in a spacecraft may not present the same technology maturity at the start of the spacecraft development. In this subsection, we consider cases of spacecraft portfolios with instruments that have different initial TRLs, and investigate the impact of this heterogeneity of the technology maturity on the spacecraft mean time to delivery (*MTTD*) and its schedule risk.

1. Setting the stage: Spacecraft portfolios with two instruments

To get a preliminary idea of technology maturity heterogeneity, we first consider examples of spacecraft with only two instruments (i.e., the portfolio size is $n = 2$), and we vary the initial TRL of both instruments at the start of the spacecraft development. Figure 15 shows the Mean-Time-To-Delivery for all the 2-Instrument TRL combinations (such as ***Pf*** = [4,4], ***Pf*** = [4,6], ***Pf*** = [7,9], etc.).

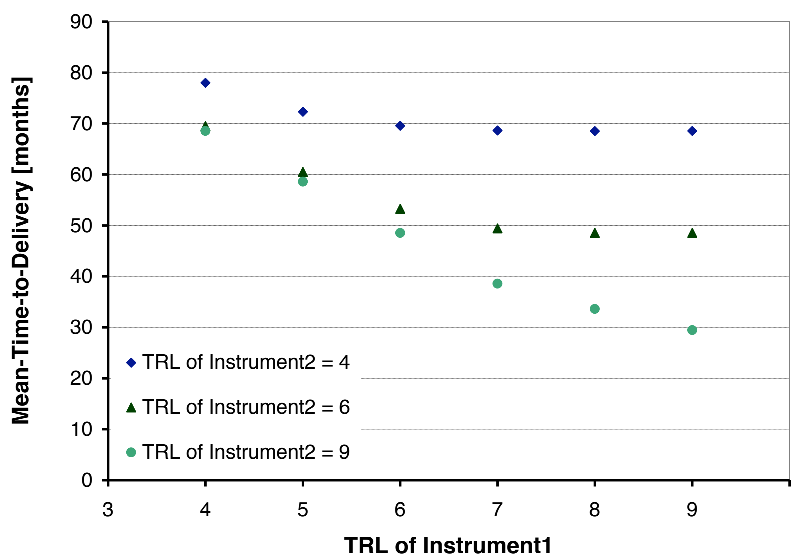

Figure 15. Mean-Time-To-Delivery for heterogeneous TRL cases with 2 Instruments

Notice on Figure 15 that when Instrument 2 has a TRL = 4, increasing the TRL of the other instrument (the x-axis) does not result in any significant reduction in the spacecraft *MTTD*. In other words, it is the least mature instrument that drives the *MTTD*. This result is expected since the Integration & Testing phase of the spacecraft can only start once *all* the instruments have been developed, as reflected by the "maximum" function in Eq. (4). In the following, we generalize this result to spacecraft with a (TRL-)heterogeneous portfolio of any size *n*.

2. Degree of TRL-heterogeneity

To continue our exploration of the concept of TRL-heterogeneity of a portfolio and its implications on the Time-to-Delivery of a spacecraft, $TD_{s/c}$, we introduce the following metric to measure this degree of TRL-heterogeneity:

$$\delta = \sqrt{\frac{1}{n}\sum_i (TRL_i - \mu_{TRL})^2} \quad \textbf{(12)}$$

n is the portfolio size, μ_{TRL} is the average initial TRL of all the instruments in the portfolio, and TRL_i is the specific TRL of instrument i. The degree of heterogeneity δ is the standard deviation of the instruments TRLs in the portfolio.

Two observations are in order. First notice than when $\delta = 0$, all the instruments in the portfolio have the same average TRL, and as a result, this becomes the homogeneous TRL case discussed in IV-A. Second, it should be pointed out other measures of the degree of TRL-heterogeneity can be defined, such as the average L1 norm of the deviations from the mean TRL:

$$\delta' = \frac{1}{n}\sum_i \left|TRL_i - \mu_{TRL}\right|$$

The definition in Eq. (12) was selected over the latter as it provided more "resolution" and yielded more spread values to reflect the diversity of portfolio configurations than the latter. We believe however that both measures are equally valid.

As an application of Eq. (12), consider the following two portfolio vectors:
$\boldsymbol{Pf_1}$ = [6 6 6 6 6 6] and $\boldsymbol{Pf_2}$ = [4 5 5 7 7 8].
Both of them have the same average TRL μ_{TRL}= 6. The degree of TRL-heterogeneity of the first is $\delta_1 = 0$ and of the second $\delta_2 = 1.4142$. Furthermore, many combinations of 6 instruments with different TRL can form portfolios with an average TRL of 6.

If responsiveness is an issue for a particular program, or if it is important that a system be fielded sooner rather than later, then the following question may emerge during the design down-selection process: which portfolio selection will result in a spacecraft that is most likely to be delivered the earliest?

The TRL-heterogeneity measure (δ) allows us to extend the analysis with only two instruments in a spacecraft (n = 2) to any value of its portfolio size. The results for n = 6 are provided in Figure 16a and Figure 16b. The results show a clear and strong positive correlation between the Mean-Time-To-Delivery of a spacecraft (*MTTD*) and its degree of TRL-heterogeneity (δ), as well as between the Schedule Risk (shown on Fig.14b is $SR_{0.5}$) and δ. For example, the spacecraft with the most heterogeneous portfolio in Fig. 14a ($\boldsymbol{Pf_3}$ = [4 4 4 6 9 9] with $\delta_3 = 2.2361$) takes on average 102 months to be delivered, whereas a spacecraft with similar portfolio size and average TRL (i.e., the TRL-homogeneous case $\boldsymbol{Pf_1}$ = [6 6 6 6 6 6] and $\delta_1 = 0$) takes on average 78 months to be delivered. This represents a significant 31% reduction in the *MTTD* of the spacecraft by simply pulling on the degree of TRL-heterogeneity lever to achieve better responsiveness, and without changing the number of instruments (portfolio size) for the spacecraft.

The changes in Schedule Risk due to the spacecraft TRL-heterogeneity are even more significant than the changes in *MTTD* (Figure 16b). For example, the Schedule Risk $SR_{0.5}$ (likelihood of overshooting the *MTTD* by 6 months) increases from 1% for $\boldsymbol{Pf_1}$ to 34% for $\boldsymbol{Pf_3}$.

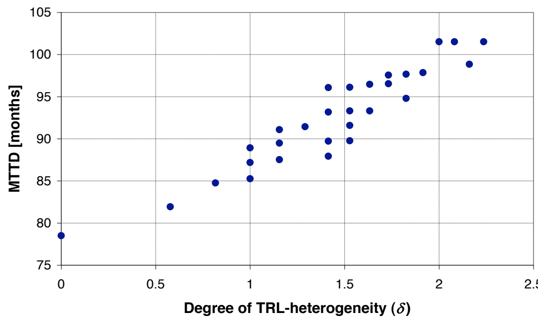

Figure 16a. Mean-Time-To-Delivery as a function of the degree of TRL-heterogeneity (δ) (n = 6, and μ_{TRL}= 6)

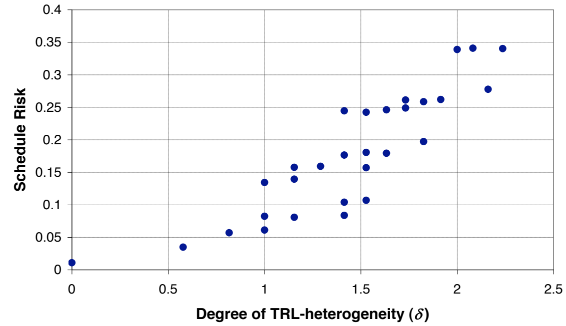

Figure 16b. Schedule Risk (mr = 6 months) as a function of the degree of TRL-heterogeneity (n = 6, and μ_{TRL}= 6)

In conclusion, this analysis confirms the intuition that it is more advantageous from a schedule standpoint (*MTTD* and schedule risk) to select spacecraft portfolios with instruments of similar (δ= 0) or roughly similar initial technology maturities (δ < 1), rather than TRL-heterogeneous portfolios with both high and low maturity instruments.

V. Utility Implications of Spacecraft Time-to-Delivery and Portfolio Selection

A. Definition of utility

The motivation for the adoption of a portfolio approach consists in the ability to select a bundle of projects (here, instruments in a spacecraft) and carefully plan their development over time in order to guide the proper overall trade-offs between return on investment and hedging against downside risks. Successful companies using this approach typically constitute their R&D portfolio according to a set of short-term, medium-term and long-term goals. In this section, we propose to analyze the cumulative utility provided by the spacecraft (through its instruments) and identify the portfolio for which, given a time-horizon τ_{ops}, this spacecraft utility is maximized. This analysis here provided constitutes an important step towards the development of a value-centric design methodology (VCDM) for unpriced systems value (e.g., military or scientific systems, the services of which are not priced in a market).[39,40] Utility is here defined as a scalar that represents the satisfaction derived from the services provided by the system to the customer per unit time. Recall that $TD_{s/c}$ captures the total time elapsing from the beginning of instruments development until the spacecraft launch. (For our utility analysis, we neglect the time needed to perform on-orbit check-ups before the spacecraft is delivered to the customer and starts providing service). As a result, we can use the model of spacecraft Time-to-Delivery presented in Section III, that is, $TD_{s/c}$ months after the start of the development for the spacecraft to begin delivering services. In the following, we run our analysis for the calculation of the cumulative utility starting from $TD_{s/c}$, until the time-horizon τ_{ops} of interest is reached, as shown in Figure 17.

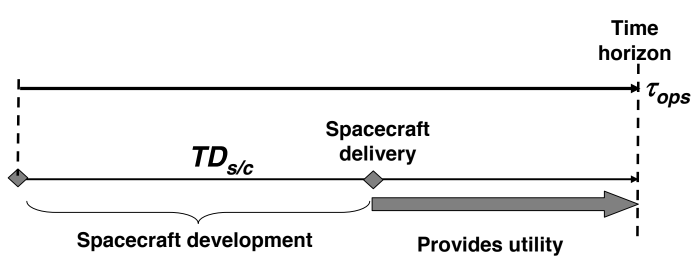

Figure 17. Utility provided by the spacecraft until the time-horizon is reached (illustrative)

By analogy with the definition of the spacecraft as a Technology Portfolio in Eq. (3), we define the instantaneous utility of the spacecraft as the vector composed of the utility per unit time provided by each instrument:

$$\hat{\mathbf{u}}_{s/c} = [\hat{u}_1 \quad \hat{u}_2 \quad \ldots \quad \hat{u}_n] \tag{13}$$

The values of the $\hat{u}_i$ components can be tuned to reflect that an instrument is more "useful" than others. For the sake of simplicity, they have all been set to 1 in the analysis presented below. When operational, the spacecraft provides a total utility per unit time that is:

$$\hat{u}_{tot} = \sum_i \hat{u}_i \tag{14}$$

As illustrated in Figure 17, the spacecraft starts delivering utility once it has been delivered. The cumulative utility obtained after the time-horizon τ_{ops} is thus defined as follows:

$$u = \hat{u}_{tot} \cdot (\tau_{ops} - TD_{s/c}) \cdot H(\tau_{ops} - TD_{s/c}) \tag{15}$$

$H(\tau_{ops}\text{-}TD_{s/c})$ is the Heaviside step function whose value is 0 when $\tau_{ops} < TD_{s/c}$ (the satellite has not yet been delivered) and 1 when $\tau_{ops} > TD_{s/c}$.

The following analysis considers the TRL-homogeneous case described in Section IV-A. Figure 18 represents the results obtained after running the model for various durations after the development starts (i.e., for various time-horizons τ_{ops}). Each curve in Figure 18 corresponds to a single value of the time-horizon τ_{ops}, for which the cumulative utility is plotted as a function of the number of instruments. In this example, the initial value of the TRL of the instruments is $TRL_{ini} = 4$. As expected, the cumulative utility is higher when the time-horizon is longer, since the model is allowed to run for a longer time period.

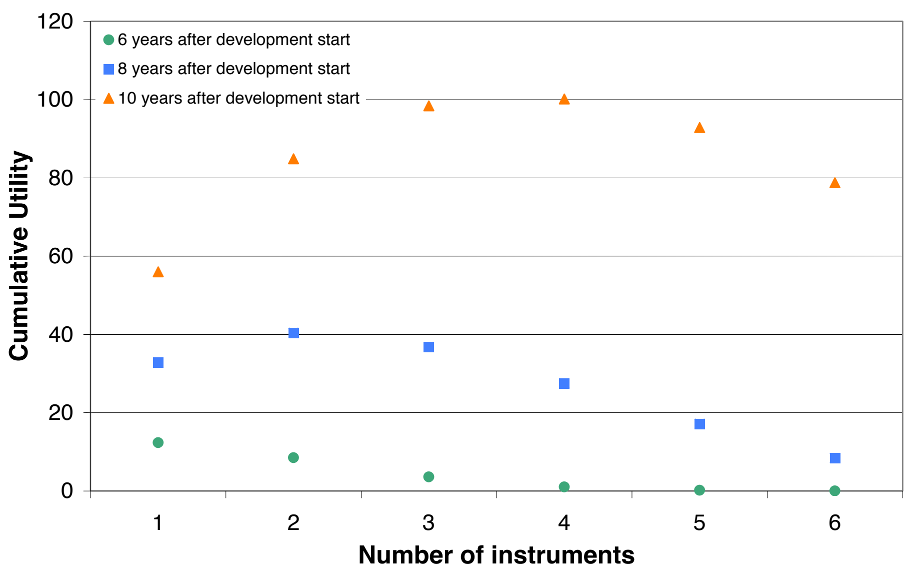

Figure 18. Cumulative utility as a function of portfolio size for different time-horizons (TRL_{ini} = 4)

More importantly, the significant result in Figure 18 is the existence of a maximal cumulative utility for a given time-horizon. For example, if the time-horizon of interest is 6 years after the development starts, we see on Figure 18 that a spacecraft with only one instrument will provide the most utility of all other spacecraft with larger portfolio sizes. Spacecraft with more instruments will take longer to develop, and as a result, their on-orbit operational time will be shorter for a given time-horizon of interest (see Figure 17 for clarifications), and, while their utility per unit time will be larger than the single-instrument spacecraft [Eqs. (13-14)], the time-horizon of interest will not allow them to reap the benefits of the larger portfolio size (i.e., will not compensate for the increase in $TD_{s/c}$).

Similarly, we read on Figure 18 that if the time-horizon of interest is 10 years, then the highest utility will be obtained by a portfolio size of 4 instruments. Larger spacecraft with more instruments cannot outperform the 4-instrument spacecraft on a utility basis.

B. The temporal paradigm shift needed to design for space responsiveness

Figure 18 and the previous discussion raise an important paradigm shift, which is needed in design optimization for responsive space. The shift addresses the onset of the hypothetical chronograph when the system utility should start being evaluated. We refer to it as calendar-based optimization, and oppose it to the traditional clock-based (after launch) spacecraft design and optimization. In the latter, one care about how much cumulative utility can be delivered n years after the delivery (or launch) of a space system. (This implies that designs are compared despite their possibly different time-to-delivery). As a result, schedule slippages are of limited relevance since the system utility starts being counted when the spacecraft is launched. However, in a calendar-based optimization, which is needed for responsive space, the clock starts ticking as soon as the need or opportunity for a space asset is identified. While the utility will be effectively delivered only when the spacecraft is launched, the same time origin (the identification of the need) is used to count utility for all the possible designs being evaluated in the optimization process. In such an environment, one cares about how much cumulative utility can be delivered n years after the identification of the need, that is, at a common calendar end date for all the designs being compared.

Figure 19 illustrates how design decisions can differ based on the mindset in which the optimization is conducted. Consider two designs of spacecraft: one referred to as "responsive" (D1) as it yields a short time-to-delivery τ_{d1}, the second being less responsive (D2), with a longer time-to-delivery τ_{d2}, but offering a higher utility potential (e.g., a bigger spacecraft with more instruments, low TRL technologies but offering performance improvements, etc.).

- In the clock-based mindset, the cumulative utility after n years following the launch only reflects the difference of utility potential between the designs, and does not take their responsiveness into account. In other words, the time-to-delivery of the spacecraft $TD_{s/c}$ does not affect the spacecraft design choices. As a result, in a clock-based design environment, a larger spacecraft (D2) will always be better on a utility basis than a smaller one with fewer instruments (D1).

- In the calendar-based mindset, $TD_{s/c}$ becomes a critical duration and the choice of the time-horizon τ_{ops} (end calendar date) determines how much importance is attributed to responsiveness. As a result, more responsive designs (D1), even if they offer a lower utility potential, will provide a higher cumulative utility than less responsive designs (longer time-to-delivery τ_{d2}) when the time horizon is reached. Therefore, in a calendar-based design environment (i.e., for space responsiveness), bigger spacecraft are not necessarily better.

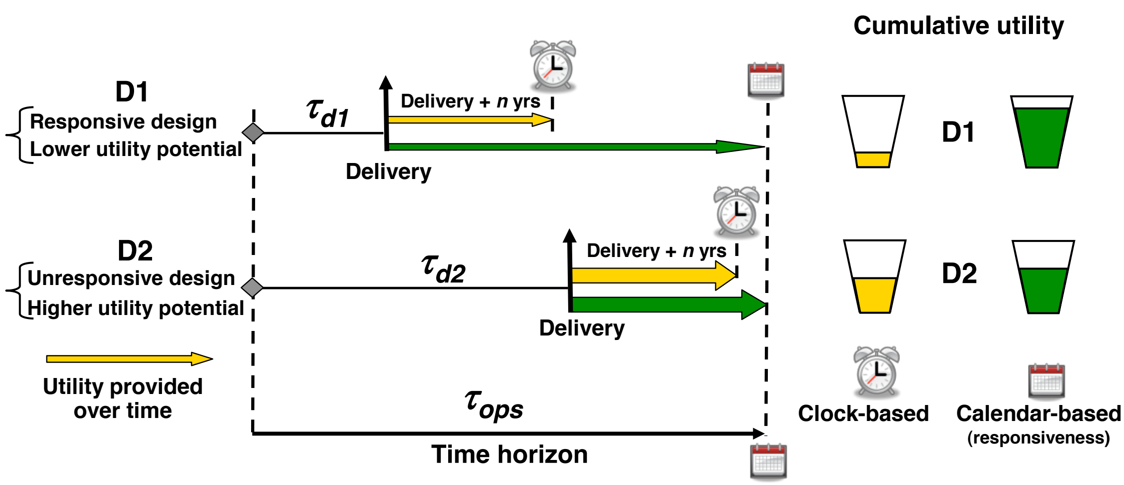

Figure 19. The paradigm shift needed to design for Responsive Space

C. Optimal portfolios in the calendar-based design paradigm

The proper portfolio characteristics in a calendar-based design environment are contingent on the time horizon of interest to the decision-makers, and address not only the size of the portfolio, but also its technology maturity and TRL-heterogeneity, as will be discussed next. The "utility-optimal" portfolio size in a calendar-based design environment is shown in Figure 20.

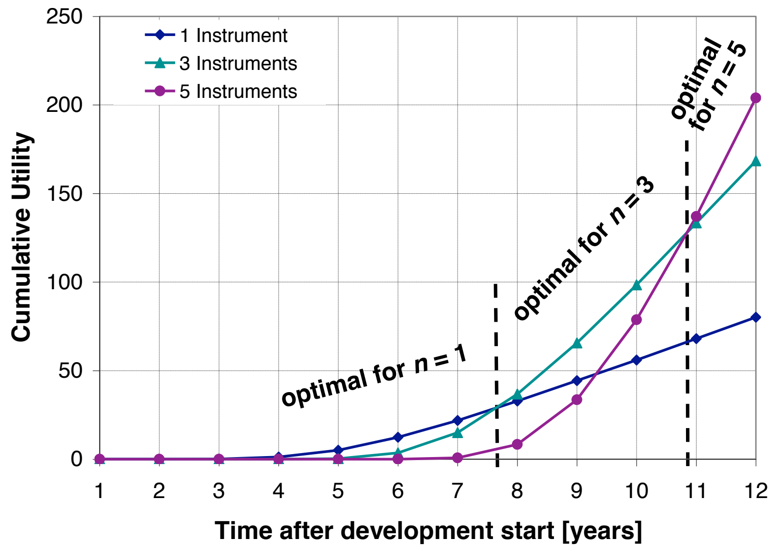

Figure 20. Cumulative utility over time after development starts, for various portfolio sizes (TRL_{ini} = 4)

Using the utility results in Figure 18, we can identify "optimal" portfolio sizes that provide the highest utility based on the time-horizon considered. The results are shown in Figure 20, for various portfolio sizes, namely $n = 1$, $n = 3$ and $n = 5$ (and a homogeneous portfolio with instruments $TRL_{ini} = 4$). The three utility curves intersect at different times, and these intersection points allow the identification of time regions where the use of a given portfolio size is more beneficial in terms of utility. For example, when the time-horizon of interest is less than 8 years, a single-instrument spacecraft will provide more utility than spacecraft with the other portfolio sizes considered (see the first intersection point in Figure 20). On the other hand, if the time-horizon of interest is greater than 11 years, then a spacecraft with 5 instruments will provide more utility than ones with $n = 1$ and $n = 3$ (see the third intersection point in Figure 20).

Next, we add the TRL dimension, in addition to the time-horizon τ_{ops} to our search of the utility-optimal portfolio size. Recall that the curves in Figure 18 and Figure 20 were derived for a single value of the initial instruments TRL ($TRL_{ini} = 4$). The initial technology maturity level of the instruments affects the delivery schedule of the spacecraft (as seen in Figure 13a), which in turn affects the cumulative utility provided after a given period. The location of the intersection points of Figure 20 is therefore dependant on the initial TRL of the instruments.

The results for the utility-optimal portfolio size as a function of the instruments TRL and the time-horizon are shown in Figure 21. Figure 21 shows the location of the intersection points for different values of the instruments TRL and provides the utility-optimal portfolio sizes that maximize the cumulative utility over varying time-horizons. Different readings can be made of Figure 21. For example, if instruments considered for inclusion on a spacecraft have an initial $TRL_{ini} = 8$, then a portfolio with 5 instruments will provide the most utility for time-horizons greater than 6 years. If one is interested in a short time-horizon of 3 years, a single instrument spacecraft will provide the highest utility. One final reading of Figure 21 is worth pointing out: if a program is keen on including low-TRL instruments, say $TRL_{ini} = 4$, the development schedule will be significantly stretched. In that case, it would almost take 11 years for a spacecraft with $n = 5$ instruments to reveal its benefits in terms of cumulative utility compared to a smaller spacecraft. Thus it seems preferable if low TRL instruments are necessary for inclusion in a spacecraft, to have smaller portfolio than larger ones (i.e., fewer instruments on-board—recall this observation is based on the TRL-homogeneous case).

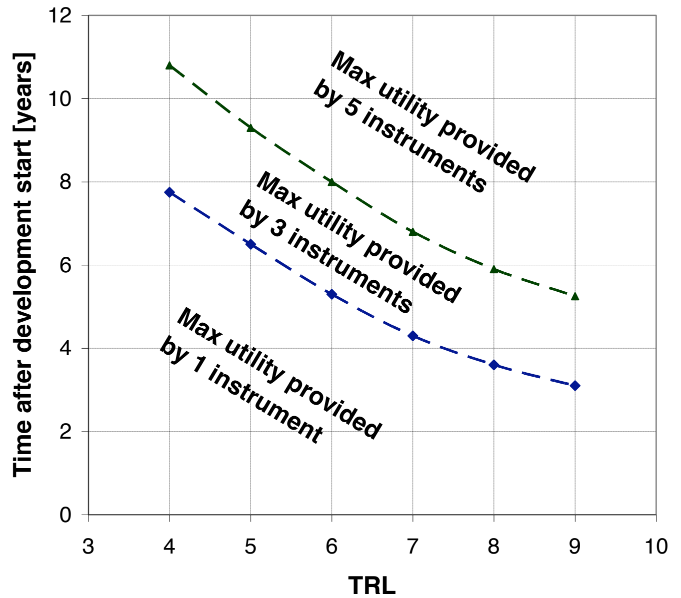

Figure 21. Map of optimal portfolio sizes yielding the maximum cumulative utility

Next, we add the degree of TRL-heterogeneity and evaluate all possible of portfolio combinations (by varying both n and δ). The results for τ_{ops} = 12 years are shown in Figure 22 in the cumulative utility versus *MTTD* space.

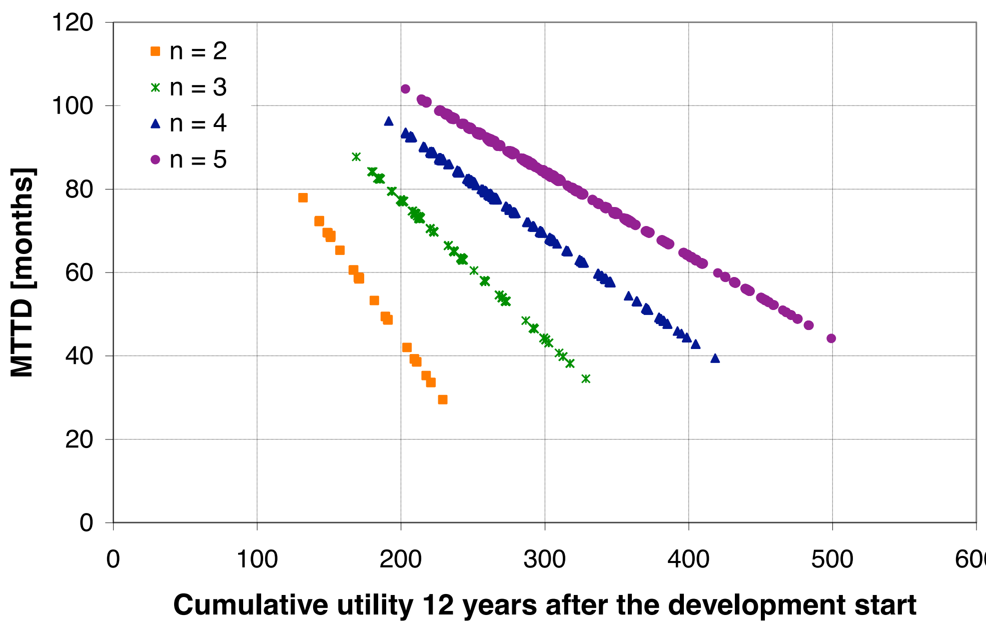

Figure 22. Cumulative utility versus MTTD for all portfolio combinations (for τ_{ops} = 12; shown on the figure are portfolio sizes $2 \leq n \leq 5$)

Two important observations are highlighted based on Figure 22:

- For each portfolio size n (a given "line"), the bottom-right combination corresponds to the spacecraft that will provide the most utility after 12 years and will be delivered the earliest. These portfolio combinations tend to have the highest average TRL and lowest degree of TRL-heterogeneity.

- If responsiveness is a high-priority goal of a space program, then schedule constraints can be specified by limiting the maximum *MTTD* allowable. This would be reflected by a horizontal line (threshold) in Figure 22, which the spacecraft development time should not exceed. This results in the exclusion of all the portfolios that yield a longer *MTTD* (the subset of portfolios "points" that are above the required *MTTD* threshold). For example, if a spacecraft has to be delivered in less than 40 months, no portfolio combination with four or more instruments will satisfy this condition. The final selection of the "best portfolios" can then be made among the remaining candidates, based on tradeoffs between utility, cost, and other metrics of interest to the customer (which would require similar analyses along the other dimensions). In addition, Figure 22 can be used to identify the reduction in *MTTD* if one or more instruments are removed from the spacecraft portfolio.

Finally, it should be noted that these results are based on the assumption of a homogeneous utility per instrument and across TRLs (assumption stated between Eq. (13) and (14)). This in reality need not be the case and the coefficients in the utility vector $\hat{\mathbf{u}}_{s/c}$ can be tuned differently to reflect different instantaneous utilities provided by different instruments considered for the spacecraft. To capture the value of innovation, the utility provided by instruments using brand new technologies (and thus characterized by a low TRL) would be considered higher than that one of more traditional instruments. Such adjustments would modify the shape of the set of points presented in Figure 22, but would not alter its use and interpretation.

VI. Conclusion

Addressing the challenges of Responsive Space and mitigating the risk of schedule slippage require a thorough understanding of the various factors driving the development schedule of a space system. The technology maturity of spacecraft subsystems and payload instruments (as measured by the TRL) has been identified as a major driver of schedule for space programs. However, various parameters, other than TRL, affect the variability of schedule slippage across multiple space programs and should therefore be investigated along with the technology maturity. To do so, we adapted the notion of portfolio developed by the R&D community to the micro-level of a single complex engineering system by conceiving of a *spacecraft itself* as a technology portfolio. We focused on the characteristics of this portfolio, namely its size (e.g., number of instruments), the technology maturity of each instrument, and the resulting TRL heterogeneity of the portfolio. As the development schedule of a spacecraft is subject to numerous sources of uncertainty, we formulated a probabilistic model of the Time-to-Delivery of a spacecraft, which includes the development, Integration and Testing, and Shipping phases. The resulting random variable Time-to-Delivery (along with its mean and dispersion) is one important characterization of space responsiveness and schedule risk.

By varying the portfolio characteristics, we investigated how the Mean-Time-To-Delivery (*MTTD*) of the spacecraft and schedule delivery risk are affected by the choice of the spacecraft technology portfolio. Results of the Monte-Carlo simulations confirmed that the *MTTD* and schedule risk of the spacecraft increase when the initial TRL of the instruments is lower, and that, for a given maturity level, the *MTTD* of the spacecraft increases when the number of instruments increases. Furthermore, the framework we developed proved useful to highlight "portfolio effects" resulting from the joint impact of the portfolio size and the individual technology maturities of the instruments. Specifically, it was found that the influence of the portfolio size on the *MTTD* is more significant at low TRL. Also, we defined the concept of degree of TRL-heterogeneity of the portfolio, whose application revealed that systems with homogeneous portfolios of instruments were delivered sooner and were subject to less schedule risk than heterogeneous ones. Finally, we explored the utility implications of varying the portfolio characteristics and time-horizons, and provided "portfolio maps" as guides to help system designers identify appropriate portfolio characteristics. A critical paradigm shift needed for designing for space responsiveness was then identified: when operating in a calendar-based environment (i.e., for a given time-horizon after the start of development), larger spacecraft with more instruments are not necessarily providing more cumulative utility than smaller ones, as their delivery to the customer is more likely to be delayed.

We believe the concept of "spacecraft portfolio" is essential to conduct value-centric design, that it is particularly important in a calendar-based design environment (such as required for space responsiveness), and that it can help the space industry make better value and risk-informed design and acquisition choices. The specific portfolio dimensions of a spacecraft presented in this paper should prove useful for mitigating schedule risk and slippage in space programs, and ultimately enhancing mission responsiveness.

Appendix

In this appendix, we provide a justification of the use of lognormal distributions for the three schedule models developed previously, namely the model of Instrument Delivery Schedule [Eq. (2)], the model of Integration & Testing Schedule, T_{int} [Eq. (6)], and the model of the spacecraft shipping time T_{ship} [Eq. (8)].

To test the appropriateness of lognormal distributions for these schedule-related random variables, we display the data in what is referred to in statistics as "probability plots". Probably plots provide a quick and efficient visual test of whether data or observations of a random variable arise from a particular parametric distribution (e.g., exponential, lognormal), or if the considered parametric distribution is a good approximation (or mathematical model) for the data. Typically, values of the random variable of interest would be represented along the x-axis, while the cumulative probabilities associated with these values would span the y-axis. Probably plots however introduce a simple and most useful variation to this graphical representation: instead of these variables, a probability plot represents a particular change of variables such that, if the empirical data is aligned in say a lognormal probability plot, then the data indeed arises from a lognormal distribution or can be properly approximated by a lognormal distribution. The details of the particular change of variables can be found in various statistical analysis textbooks, [41,42] and the specifics of Weibull probability plots can be found in Ref. 43.

For each of the three input models used in this paper to derive the primary output of interest $TD_{s/c}$, we provide the lognormal probability plots based on the data available (limited in some cases) to justify the use of lognormal distributions as good approximation for the input random variables in our analysis.

A. Model of Integration & Testing

Figure 23a shows a lognormal probability plot for the data set of 21 NASA spacecraft used in Section III.B to model the duration of the Integration & Testing phase. When all portfolio sizes are considered, Figure 23a reveals that with the exception of one outlier, a lognormal distribution is an acceptable model of the I&T phase. Recall though that for each value of the portfolio size, a specific lognormal distribution was used, as described in Eqs (6) and (7). For example, consider the case n = 3 instruments: for this subset of spacecraft, Figure 23b provides a lognormal probability plot that shows a good alignment of the data along the lognormal line.

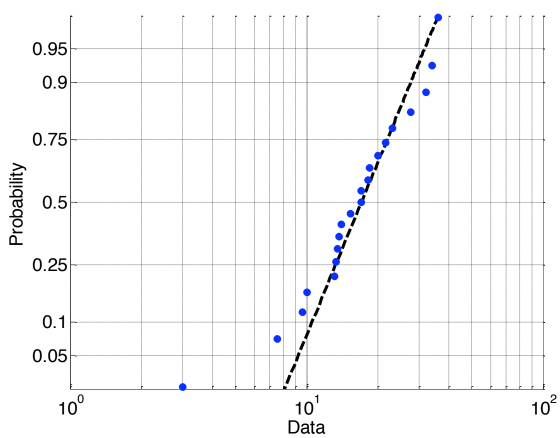

Figure 23a. Lognormal probability plot for duration of Integration & Testing (all portfolio sizes)

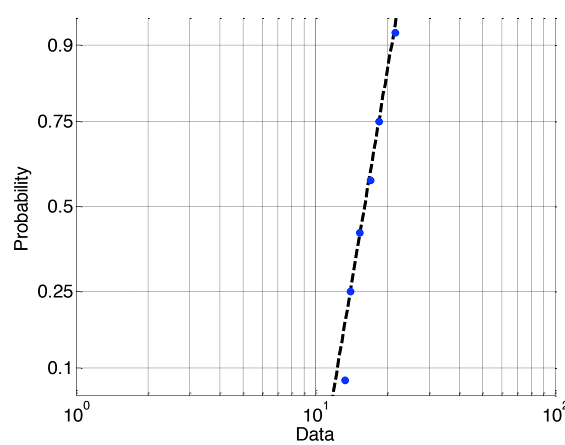

Figure 23b. Lognormal probability plot for duration of Integration & Testing (only n = 3)

As a result, lognormal distributions for the I&T phase (based on the available data of the 21 NASA spacecraft used in this paper) are good approximations for the duration of this phase. More formal methods for the justification of the lognormal distribution are not relevant for the purpose of this study, but they would constitute useful future work if a larger dataset was available.

B. Model of Spacecraft Shipping phase duration

We modeled in section III.C the duration of the shipping phase using a single lognormal distribution. Figure 24 shows the corresponding lognormal probability plot for the 21 spacecraft of the dataset. While the data is roughly aligned for the larger durations, a noticeable divergence from a pure lognormal distribution is visible for four data points with the shortest durations of shipping. While these data points cannot be ruled out as outliers, their parametric modeling requires advanced statistical techniques that are beyond the scope and purpose of this study.

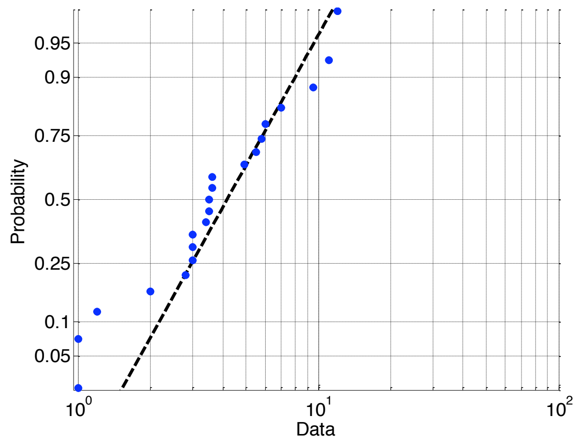

Figure 24. Lognormal probability plot for duration of Shipping

In conclusion, while we do not claim that lognormal distribution is the ideal parametric distribution to model the duration of the shipping phase, it provides nevertheless a reasonable approximation of the duration of this phase.

C. Development schedule in relation with TRL

Very limited schedule data in relation to TRL exist in the literature. For this reason, the data presented in Dubos et al.[5] is used to provide an indication of schedule distribution in relation to technology maturity. This data set included 28 NASA spacecraft for which total schedule duration as well as average system-TRL were available. Figure 25a represents a lognormal probability plot for the total schedule of all the NASA spacecraft, regardless of the initial system-TRL. As a preliminary result, this figure shows that lognormal distribution is a legitimate model of the total schedule of spacecraft development in a general sense.

Furthermore, this assumption remains valid when subcategories of spacecraft based on initial technology maturity are considered. As an example, Figure 25b shows a lognormal probability plot for the subset of spacecraft characterized by an average TRL value of 5. The fairly good alignment of the data points with the lognormal line confirms the legitimacy of the use of a lognormal distribution per category of TRL.

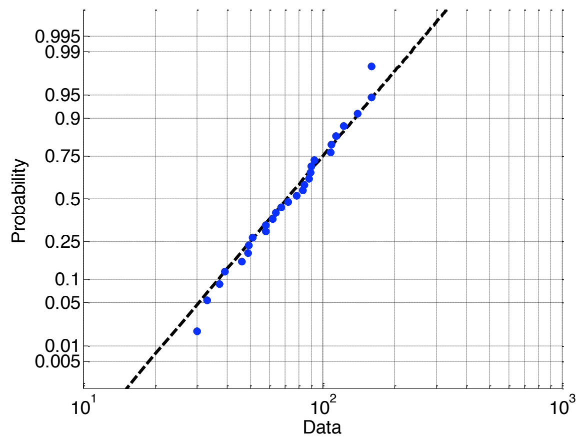

Figure 25a. Lognormal probability plot for total schedule (all TRLs)

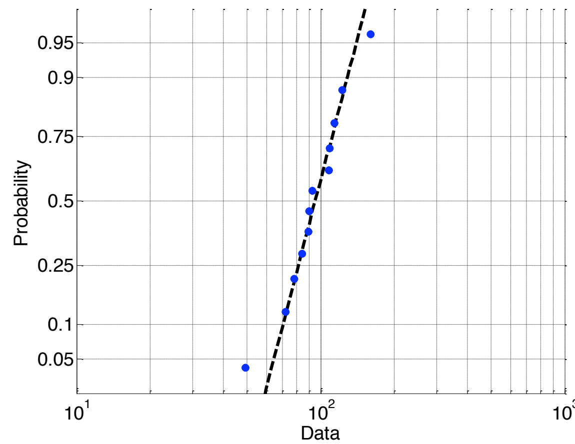

Figure 25b Lognormal probability plot for total schedule (only systems with system TRL = 5)

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