STOCHASTIC MODELING OF RESPONSIVENESS, SCHEDULE RISK AND OBSOLESCENCE OF SPACE SYSTEMS, AND IMPLICATIONS FOR DESIGN CHOICES

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STOCHASTIC MODELING OF RESPONSIVENESS, SCHEDULE RISK AND OBSOLESCENCE OF SPACE SYSTEMS, AND IMPLICATIONS FOR DESIGN CHOICES

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NOMENCLATURE

AFRL = Air Force Research Laboratory
AHP = Analytic Hierarchy Procedure
AO = Announcement of Opportunity
ANSI = American National Standards Institute
BEA = Bureau of Economic Analysis
BTI = Built-to-Inventory
BTO = Built-to-Order
CADRe = Cost Analysis Data Requirement
CRO = Calendar Risk of On-Orbit Obsolescence (dynamic)
DMSMS = Diminishing Manufacturing Sources and Material Shortages
DOD = Department of Defense
DSK = Dvorak Simplified Layout
EAR = Export Administration Regulations
EIA = Electronic Industries Associations
FAA = Federal Aviation Administration
FCC = U.S Federal Communications Commission
FDM = Fuzzy Delphi Method
FTD = Final Total schedule Duration
GAO = Government Accountability Office
GUI = Graphical User Interface
I&T = Integration & Testing
IDE = Initial schedule Duration Estimate
IDS = Instruments Delivery Schedule
IOC = Initial Operational Capability
IRL = Integration Readiness Level
ITAR = International Traffic in Arms Regulations
ITI = Integrated Technology Index

IXO = International X-Ray Observatory
LRO = Lifetime Risk of On-Orbit Obsolescence (dynamic)
MAV/MAU = Multi-Attribute Value/Utility
MDR = Mission Definition Review
mO = minor Obsolescence state
MO = Major Obsolescence state
MTTD = Mean-Time-to-Delivery
NASA = National Aeronautics and Space Administration
NPD = New Product Development
NPV = Net Present Value
PDR = Preliminary Design Review
PnP = Plug and Play
ORS = Operationally Responsive Space
OSI = Open Systems Interconnect
R&D = Research and Development
R&D^3 = Research and Development Degree of Difficulty
RFI = Request For Information
RFP = Request For Proposal
RSS = Relative Schedule Slippage
S&T = Science & Technology
SAR = Synthetic Aperture Radar
SBIRS = Space Based Infrared System High
SoA = State-of-the-Art state
SPN = Stochastic Petri Net
SRL = System Readiness Level
SRO = Static Risk of On-Orbit Obsolescence
ST6 = Space Technology 6
TAA = Technical Assistance Agreement
TFN = Triangular Fuzzy Number
THESIS = Terrestrial and Habitable-zone Exoplanet Spectroscopy Infrared Spacecraft

TNV = Technology Need Value
TRL = Technology Readiness Level
Tr.FN = Trapezoidal Fuzzy Number
USML = United States Munitions List
VCDM = value-centric design methodology
WTRL = Weighted average TRL

SUMMARY

The U.S Department of Defense and the National Aeronautics and Space Administration continue to face common challenges in the development and acquisition of their space systems. In particular, space programs repeatedly experience significant schedule slippages, and spacecraft are often delivered on-orbit several months, sometimes years, after the initially planned delivery date. The repeated pattern of these schedule slippages suggests deep-seated flaws in managing spacecraft delivery and schedule risk, and an inadequate understanding of the drivers of schedule slippages. Furthermore, due to their long development time and physical inaccessibility after launch, space systems are exposed to a particular and acute risk of obsolescence, resulting in loss of value or competitive advantage over time. The perception of this particular risk has driven some government agencies to promote design choices that may ultimately be contributing to these schedule slippages, and jeopardizing what is increasingly recognized as critical, namely space responsiveness.

The overall research objective of this work is twofold: (1) to identify and develop a thorough understanding of the fundamental causes of the risk of schedule slippage and obsolescence of space systems; and in so doing, (2) to guide spacecraft design choices that would result in better control of spacecraft delivery schedule and mitigate the impact of these “temporal risks” (schedule and obsolescence risks).

To lay the groundwork for this thesis, first, the levers of responsiveness, or means to influence schedule slippage and impact space responsiveness are identified and analyzed, including design, organizational, and launch levers. Second, a multidisciplinary review of obsolescence is conducted, and main drivers of system obsolescence are identified. This thesis then adapts the concept of a technology portfolio from the macro- or company level to the micro-level of a single complex engineering system, and it analyzes a space system as a portfolio of technologies and instruments, each technology with its distinct stochastic maturation path and exposure to obsolescence. The selection of the spacecraft portfolio is captured by parameters such as the number of instruments, the initial technology maturity of each technology/instrument, the resulting heterogeneity of the technology maturity of the whole system, and the spacecraft design lifetime. Building on the abstraction of a spacecraft as a portfolio of technologies, this thesis then develops a stochastic framework composed of two main analysis and simulation modules: (1) The development module models the technology maturation process of each instrument as well as the integration, testing and shipping of the entire spacecraft, producing estimates of the spacecraft time-to-delivery and schedule risk; (2) The operations module then models the risk of on-orbit obsolescence by simulating the evolution of the state of obsolescence of the spacecraft instruments/subsystems over time. The complete framework provides a powerful capability to simultaneously explore the impact of design decisions on spacecraft schedule, on-orbit obsolescence, and cumulative utility delivered by the spacecraft. Specifically, this thesis shows how the choice of the portfolio size and the instruments Technology Readiness Levels (TRLs) impact the Mean-Time-To-Delivery (MTTD) of the spacecraft and mitigate (or exacerbate) schedule risk. This work also demonstrates that specific combinations/choices of the spacecraft design lifetime and the TRLs can reduce the risk of on-orbit obsolescence. This thesis then advocates for a paradigm shift towards a calendar-based design mindset, in which the delivery time of the spacecraft is accounted for, as opposed to the traditional clock-based design mindset. The calendar-based paradigm is shown to lead to different design choices, which are more likely to prevent schedule slippage and/or enhance responsiveness and ultimately result in a larger cumulative utility delivered. Finally, missions scenarios are presented to illustrate how the framework and analyses here proposed can help identify system design choices that satisfy various mission objectives and constraints (temporal as well as utility-based).

CHAPTER 1

INTRODUCTION

"Mora cogitationis diligentia est."
"Le retard employé à réfléchir tient lieu de diligence."
"To take your time while planning is due diligence."

Publilius Syrus, *Sententiae* – Ist century BC.

1.1 Motivation

The U.S Department of Defense (DOD) and the National Aeronautics and Space Administration (NASA) continue to experience common challenges in the development and acquisition of their space systems. In particular, space programs repeatedly experience significant schedule slippages, and spacecraft are often completed and delivered on-orbit several months, sometimes years, after the initially planned delivery date. The Government Accountability Office (GAO) has highlighted the difficulties encountered by the DOD in keeping the acquisition of space systems on schedule (and within budget):

> "*DOD's space system acquisitions have experienced problems over the past several decades that have driven up costs by hundreds of millions, even billions, of dollars;* ***stretched schedules by years****; and increased performance risks. In some cases, capabilities have not been delivered to the warfighter* ***after decades of development****."* [1]

Figure 1 shows the delays or schedule slippage for five DOD programs, as of April 2007. The reader is referred to the GAO-07-406SP [2,3] for details about these programs. All five programs 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.

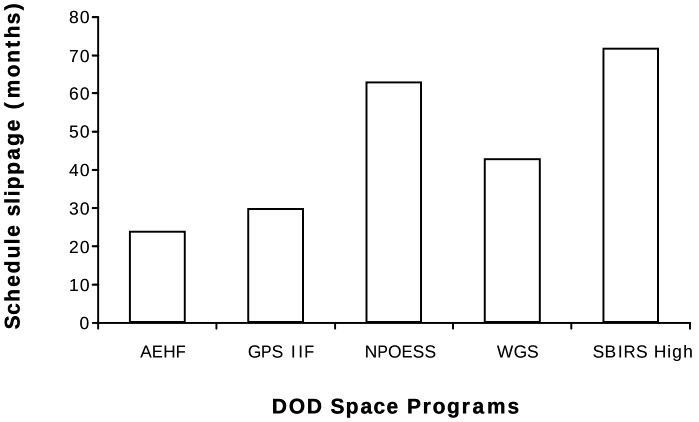

Figure 1. Delays and schedule slippage since program start (adapted from GAO-07-730T)

In addition to the schedule difficulties experienced by DOD space programs, GAO has also highlighted similar schedule growth problems with NASA missions over the last decade [4]. 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.

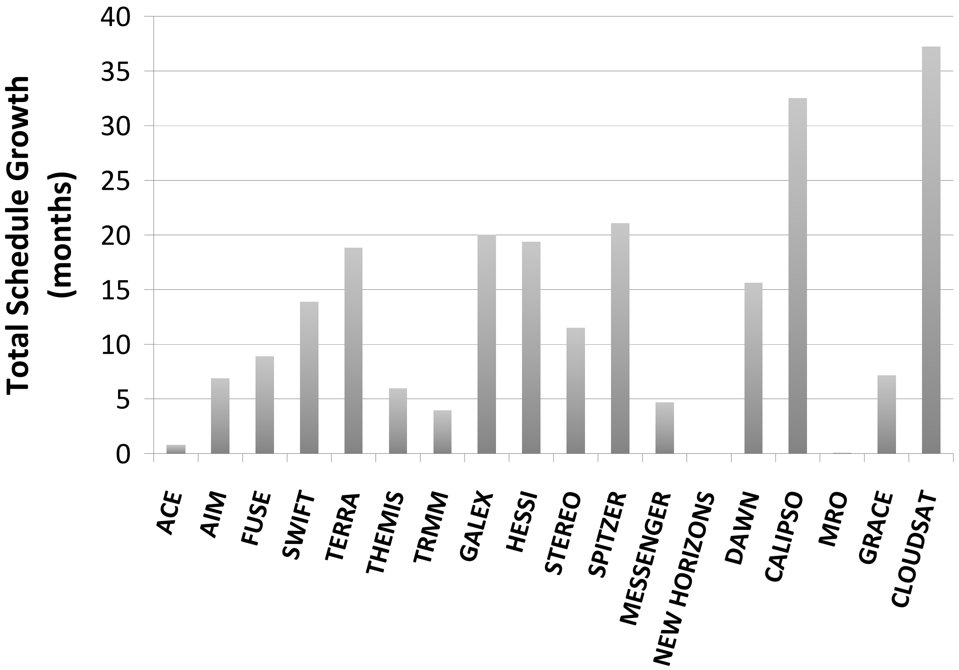

Figure 2. Schedule growth for various recent NASA missions

To explain the significance and persistence of such schedule slippages, several government reports published in the past two decades have emphasized the impact of programmatic and organizational deficiencies on the schedule of space programs.

First, numerous management and staffing changes are likely to occur over the long development time of such programs, at the organization level (NASA or DOD), at the legislative level (Congress) as well as at the executive level (Office of the U.S President). Such variations are often associated with funding instabilities that have been found to result in significant program delays. For example, the GAO describes the case of the Chandra X-ray Observatory (initially named AXAF), whose budget was cut by “about $26 million and $76 million in fiscal years 1991 and 1992, respectively” to allow funding for the Hubble Space Telescope. “These cuts caused cost increases of about $90 million because the program had to be rephased. After rephasing, Congress reduced fiscal year 1992 development funding by $60 million and significantly reduced funding for fiscal year 1993. These latter budget cuts delayed the launch from early 1998 to mid-1999" [5] (representing a year and a half of delay).

Second, over optimism and unrealistic cost estimates have also been identified as a driver of cost and schedule growth. The 2003 report of the U.S Defense Science Board/Air Force Scientific Advisory Board Joint Task Force on Acquisition of National Security Space Programs [6] stated that "unrealistically low projections of program cost and lack of provisions for management reserve seriously distort management decisions and program content, increase risks to mission success, and virtually guarantee program delays." In 1992, the GAO reported that NASA had been experiencing similar issues: "unrealistic contractor estimates" coupled with a culture of optimism was leading "the program team to underestimate technical challenges and overestimate its capabilities to solve them", which often resulted in schedule slippages [5].

Finally, the DOD also highlighted the recent and dramatic increase of systems requirements (due to a multiplication of users of space assets since the 1990's) and in many cases, the poor control of these requirements during program implementation (requirements creep) [6]. Such difficulties associated to systems requirements have been invoked to explain some of the schedule delays experienced by many space systems. According to the GAO [7], AEHF and SBIRS-High are among the systems represented on Figure 1 that experienced a combination of the programmatic reasons mentioned above.

However, the repeated pattern of these schedule slippages, in both military and civilian contexts, suggests fundamental flaws in managing spacecraft delivery and schedule risk that are not solely restricted to programmatic issues, and probably a limited understanding of the drivers of schedule slippages. Furthermore, it is important to recognize that the management of schedule of space systems is a problem of dual nature, with the prevention of schedule slippage as one side of the coin, and the schedule compression, or responsiveness improvement, as the other side of the coin. Fundamental changes would therefore be required not only to contain or prevent these schedule slippages, but also to compress these schedules in order to make the space industry more responsive to new or evolving customer needs.

In addition, due to their long development time and physical inaccessibility (for most), space systems, unlike many other engineering systems, are exposed to a particular and acute risk of obsolescence. The high pace of technological progress is such that this exposure to obsolescence can even occur before the space systems become operational. The perception of this particular risk has driven the DOD to promote design choices that may ultimately be contributing to these schedule slippages, and jeopardizing what the DOD is recognizing as increasingly critical, space responsiveness.

1.2 Research objectives and hypotheses

The overall research objective of this thesis is twofold: (1) to identify and develop a thorough understanding of the fundamental causes of the risk of schedule slippage and obsolescence of space systems; and in so doing, (2) to guide spacecraft design choices that would result in better control of spacecraft delivery schedule and mitigate these "temporal risks" (schedule and obsolescence).

To achieve those goals, several research hypotheses are formulated. Research objectives are then devised to guide the testing of these hypotheses.

Context: Programmatic reasons, such as funding instability and requirements changes, are often the only reasons invoked to explain or excuse schedule slippage and lack of responsiveness.

- **Hypothesis 1: In addition to these programmatic considerations, architectural choices and design parameters are key determinants of spacecraft delivery, schedule slippage and responsiveness (or lack thereof).**
- **Research objective 1: Develop quantitative models and analyses to investigate the relationship between spacecraft delivery schedule and design parameters.**

Context: Each spacecraft subsystem and instrument follows its own maturation and development path, which impacts the delivery schedule and schedule risk of the whole spacecraft.

- **Hypothesis 2: Conceiving of and analyzing a spacecraft as a technology portfolio (of instruments/subsystems) will reveal insights about spacecraft delivery schedule and responsiveness, and will help make better risk-informed design decisions (in particular with respect to schedule risk).**
- **Research objective 2: Propose a theoretical framework and a probabilistic analysis of spacecraft delivery time by conceiving of it as a technology portfolio, with multiple technologies/instruments having distinct maturation**

and development paths, and by accounting for their time to integration in the ***portfolio*****.**

Context: The persistence of the issues of schedule slippage in space system development suggests that more fundamental causes are in effect, as early as in the design process, and that are common across projects.

- **Hypothesis 3: The current clock-based design optimization mindset is one major driver of the recurrent issues of schedule slippage.**
- **Research objective 3: Present the circumstances under which this clock-based calendar mindset is flawed and demonstrate the relevance of a calendar-based mindset to design for responsiveness.**

Context: The DOD asserts that the inclusion of technologies with low maturity still represents an important way of ensuring that its space systems always possesses the most advanced technologies, thus mitigating their risk of obsolescence.

- **Hypothesis 4: The risk of on-orbit obsolescence is influenced by architectural choices and design parameters, and a trade-off exists between mitigating the risk of on-orbit obsolescence and schedule risk.**
- **Research objective 4: Quantify the impact, if any, of spacecraft design parameters and technology choices, on the risk of on-orbit obsolescence. This research objective entails developing quantitative assessment of the risk of on-orbit obsolescence and identifying possible strategies for mitigating this risk as early as during the design process.**

1.3 Outline and summary of contributions

Chapter 2 presents **a literature review on responsive space** and provides **a new multidisciplinary framework for thinking about and addressing issues of responsiveness and schedule slippage in the space industry.** This framework advocates three levels of responsiveness: a global industry-wide responsiveness, a local stakeholder responsiveness, and an interactive or inter-stakeholder responsiveness. The use of "responsiveness maps" for multiple stakeholders is then introduced and motivated. "Levers of responsiveness", or means to influence schedule slippage and impact space responsiveness, are identified and discussed, and special emphasis is put on "design levers" or technical spacecraft-centric ways to improve responsiveness. Specifically, the Technology Readiness Level (TRL), a proxy for technology maturity, is an important design parameter whose impact on schedule slippage and schedule risk is investigated independently. **A univariate analysis of historical NASA data is conducted to characterize the relationship between TRL and schedule slippage and analytical models for schedule slippage as a function of TRL are provided**.

In order to account for other sources of variability in system delivery schedule, Chapter 3 adapts the idea of portfolio from the macro- or company level to the micro-level of a single complex engineering system, by **conceiving of the space system itself as a portfolio of technologies or instruments**. This idea of a spacecraft as a technology portfolio is then used to guide the **formulation of a stochastic model of spacecraft time-to-delivery**, through which the impacts of the portfolio characteristics on the Mean-Time-To-Delivery (MTTD) of the spacecraft and its schedule risk are investigated.

Preliminary results from this model support the claim that the clock-based design optimization mindset in which the space industry currently operates is one important underlying driver of these persistent schedule slippages. **A paradigm shift towards a calendar-based design mindset**, in which the delivery time of the spacecraft is accounted for, is proposed and shown to lead to different design choices that are more likely to prevent schedule slippage and enhance space responsiveness.

The issue of schedule risk, central to Chapter 2 and Chapter 3, pertains to the likelihood that a space system will not be delivered and provide a service in time to respond to customer needs. Chapters 4 and 5 explore a second type of "temporal risk" faced by spacecraft, namely **the risk of obsolescence** that jeopardizes the ability of space system to maintain a service that fulfills customer expectations.

In Chapter 4, the concept of obsolescence is discussed in a general sense, and main drivers of obsolescence are identified. **A multidisciplinary review of the phenomenon of obsolescence** is then conducted that presents how the fields of economics, operations research, bibliometrics and engineering have tackled this issue and discusses the modeling approaches that have been proposed.

Chapter 5 further continues the discussion of obsolescence by focusing on space systems, which, unlike ground-based systems that can be physically accessed and thus upgraded, face a specific risk of obsolescence, referred to in this thesis as "risk of on-orbit obsolescence". More specifically, Chapter 5 discusses the position of the Department of

Defense that 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. To assess the appropriateness of this rationale, a **Markov model for quantifying and analyzing the risk of on-orbit obsolescence** is developed and the impact of selected design parameters (including TRL) on the risk of obsolescence is investigated.

Chapter 6 integrates the models presented in Chapter 3 and 5 to explore *jointly* the impact of design choices (materialized by the selection of portfolio characteristics) on both the time-to-delivery and time-to-obsolescence of the spacecraft. The result is **an integrated framework that can help inform decisions made during the design of a spacecraft** (or series of spacecraft) for mitigating schedule and obsolescence risks.

Finally, Chapter 7 concludes this work and provides several recommendations for future research.

CHAPTER 2

ON SPACE RESPONSIVENESS AND THE ONSET OF SPACECRAFT SERVICE DELIVERY

“Rien ne m'arrête plus ; dans mon élan rapide
J'obéis au courant, par le désir poussé,
Et je vole à mon but comme un grand trait liquide
Qu'un bras invisible a lancé.”
“Nothing can stop me anymore; in my rapid impetus
I obey the current, pushed by the desire
And I fly to my goal like a long liquid stream
That an invisible arm has launched.”

Louise Ackermann, French poet, Le Nuage, *Poésies Philosophiques*, 1871.

2.1 Introduction

Customers’ needs are dynamic: they emerge in time and evolve stochastically, prompted by unfolding environmental (political, economic, and or technological) uncertainties and network externalities. The ability of an industry to address these needs in a timely and cost-effective manner is indicative of its responsiveness. In the space industry, a systemic discrepancy exists between the time constants associated with the emergence and change of customers’ needs, and the response time of the industry in delivering solutions to address these needs. The needs can consist of a new capability on-orbit for a military or a commercial customer, or a modification and repositioning of an existing on-orbit asset. When a new capability is required, from the moment when the need is identified and requirements are formalized to the time when an operational asset is delivered on-orbit, several years would typically elapse. Although different in details, other industries have struggled with conceptually similar issues, and management approaches such as just-in-time were developed in part to address the discrepancy between the rate of change of customers' needs and the ability of the industry to deliver timely solutions (better inventory management also played a role in the just-in-time emphasis).

Space responsiveness was first conceptualized in a military context, where needs can emerge as a result of an unexpected threat, and require the rapid deployment of space assets to ensure communications between allied forces, as well as surveillance of regions of interest. The time needed to respond to these new needs can therefore be critical to ensure swift tactical advantage. Conversely, important penalties can result from the late delivery of a needed capability to the battlefield. To tackle this challenge, the U.S Department of Defense issued in 2007 a report outlining the steps required to establish an Operationally Responsive Space Program Office to improve "the Nation's means to develop, acquire, field and employ space capabilities in shortened timeframes" [8].

The need for space responsiveness extends however beyond the defense community and is equally relevant in the commercial space sector. In a commercial context, responsiveness is helpful to gain and sustain a competitive advantage, for example by securing the first-mover advantage against a competing or alternate technology. Conversely, lack of responsiveness can result in an opportunity loss and hence, loss of potential revenue and value to shareholders. In addition, satellite manufacturers may be (contractually) obligated to pay penalties, "liquidated damages", if they experience schedule slippage (the opposite of responsiveness) and miss satellite delivery dates. Responsiveness is also important for scientific space missions. In the case of interplanetary missions, launch windows offer very little schedule flexibility and only occur every few months or years. The overall goal of more responsive missions in science is to provide an “increased return of science in much shorter time horizons” [9]. In certain cases, “responsive missions” would allow scientists to observe and study transient phenomena (e.g., atmospheric or astrophysical) whose duration is uncertain, shortly after they appeared [10]. In short, improving space responsiveness is important for military, commercial, and science applications in the space industry.

In the current space industry, various degrees of responsiveness are achieved depending on the purpose of the space mission. Figure 3 shows the average time-to-delivery for a sample of spacecraft launched since the 1990’s, organized by mission class: commercial communication satellites (29 spacecraft), military missions (15 spacecraft) and civil scientific missions (29 spacecraft). While commercial communication satellites are typically delivered in 2 or 3 years following the contract award, the development of defense and science spacecraft often takes longer, typically 5 years (or more). Furthermore, the delivery schedule of military and science spacecraft exhibit a higher variability than that of commercial communication satellites. (Note however that the size of the sample of military missions is almost half of that of commercial missions). Unlike military and science spacecraft that are often tailored to a specific mission and are thus typically designed around a unique payload, commercial communications satellites tend to be produced at a larger scale, with design similarities that range from the reliance on a common bus to the use of analogous payloads. In addition to this major distinction, other reasons that may explain the differences in responsiveness observed in Figure 3 are discussed extensively in this chapter.

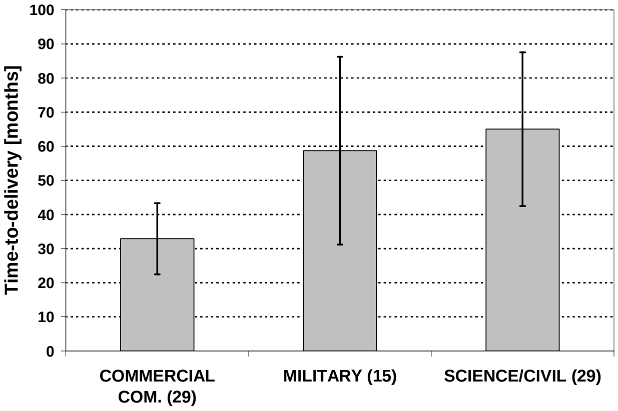

Figure 3. Average time-to-delivery of spacecraft and corresponding standard deviation bars as a function of mission class

The remainder of this chapter is organized as follows. Section 2.2 provides a definition of space responsiveness. Section 2.3 introduces a new framework for thinking about issues of space responsiveness, with three levels of responsiveness, which clarify who / what is responsive in the space industry. Section 2.4 presents tools for identifying and prioritizing responsiveness-improvement efforts. Finally, section 2.5 discusses the levers of responsiveness, or means for improving space responsiveness, including spacecraft design and operational levers, launch levers, and “soft” levers of responsiveness (e.g., acquisition policies).

2.2 Definition of space responsiveness

It is important to note that space responsiveness is a broader issue than the sole time-to-delivery of a spacecraft as shown in Figure 3. For example, in a commercial context, much time can elapse between the identification of a new need or market opportunity and the award of a contract to develop a new satellite. Similarly, the instant at which an asset is operational may not directly coincide with the instant of the launch (or the modification) of said asset. From the perspective of the end-customer or the stakeholder with the need for the space asset, **responsiveness is related to the total time τ_0 elapsed from the instance when the need for a given on-orbit capability is identified and formalized to the time when the asset is ready and operational on-orbit**. Improving space responsiveness therefore requires a thorough understanding of the schedule structure of a space asset, that is, the temporal breakdown of each activity in the space industry following the issuance of a Request For Proposal (RFP) for a new or modified on-orbit capability as well as an assessment of how much time each activity contributes to the total time τ_0. This "time accounting" is traditionally performed internally by each stakeholder for technical activities (e.g., design, manufacturing, integration and testing) in the schedule documents developed for a given space project. Other activities that should also be considered in this "time accounting" include legal, organizational and procedural activities that can often have a significant impact on the overall system delivery schedule.

Responsiveness, unlike reliability for example, is not a characteristic of an item, but a higher-level attribute of an industry's value-chain or an industry's set of customers and suppliers. Although the technical characteristics and design of the space system under development are key drivers of the space industry's responsiveness, or lack thereof, they are not its sole determinant. Other aspects have an impact on responsiveness and can be usefully tackled, along with design aspects of a spacecraft, to improve space responsiveness.

If beauty is in the eye of the beholder, responsiveness is in the eye of the "customer"; it characterizes the reaction time of "suppliers" to an external stimulation (e.g., a new order for product *X*). Figure 4 provides an illustrative representation of an industry value chain. S_i in Figure 4 are the various stakeholders in this industry and are affected when the end-customer issues a new order for a product or a service[*]. As the end-customer identifies a new need or opportunity and issues an RFP for a new asset, that RFP stirs the industry and propagates upstream its value-chain. Figure 4 illustrates the fact that there are multiple sets of "customers–suppliers" in an industry. Furthermore, one stakeholder's customer is often another stakeholder's supplier. For example, S_{22} is the "customer" of S_{221} and S_{222}, but S_{22} is also the "supplier" of S_2.

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[*] Although not important for the purpose of this chapter, a distinction is made herein between an end-customer (who issues the RFP and "pays the bill" for the whole space asset), and the end-user who pays service fees for temporary access to some on-orbit capability (e.g., a transponder). Also, note that in order to avoid cluttering Figure 4, not all the possible links among the various stakeholders are represented.

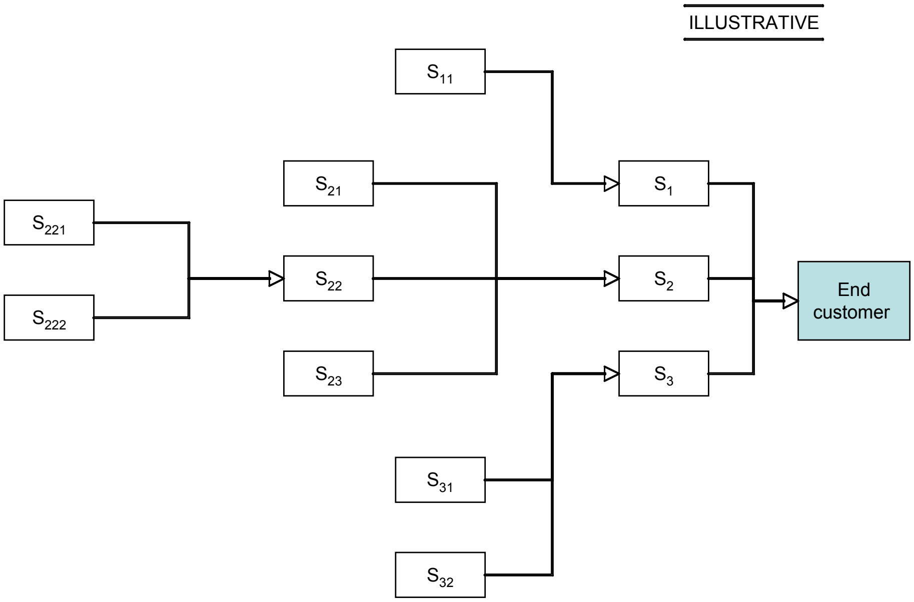


Figure 4. Illustrative representation of an industry value-chain. End customer and various stakeholders (Si). Not all links are represented.

Since responsiveness is relevant for "customers" (or stakeholders with needs), and it characterizes the reaction time of "suppliers" (or stakeholders addressing those needs, in whole or in part), different levels and types of responsiveness can be defined:

1. A *global* industry-wide *responsiveness,* as seen from the perspective of the end-customer;
2. *A local stakeholder responsiveness, as seen from the perspective of a "local" customer;*
3. An *interactive* or *inter-stakeholder responsiveness*.

2.3 The three levels of responsiveness

2.3.1 Global responsiveness

The global or industry-wide responsiveness is seen from the perspective of the end-customer who issues the RFP for a given space capability and "pays the bill" for the space asset. This is a “macro-level” attribute of the whole industry. Regardless of how the industry is structured, whether there are hundreds of suppliers or just a couple of them, from the perspective of the end-customer, what matters is the time τ_0 elapsed from the issuance of the RFP for a space asset until the asset becomes operational on-orbit. Figure 5 provides a symbolic representation of this relationship as a block diagram in which the “black box” contains all the suppliers ($\Sigma(S_i)$) that interact with the end-customer. Improving global responsiveness of an industry implies among other things reducing or compressing τ_0 as shown in Figure 6.

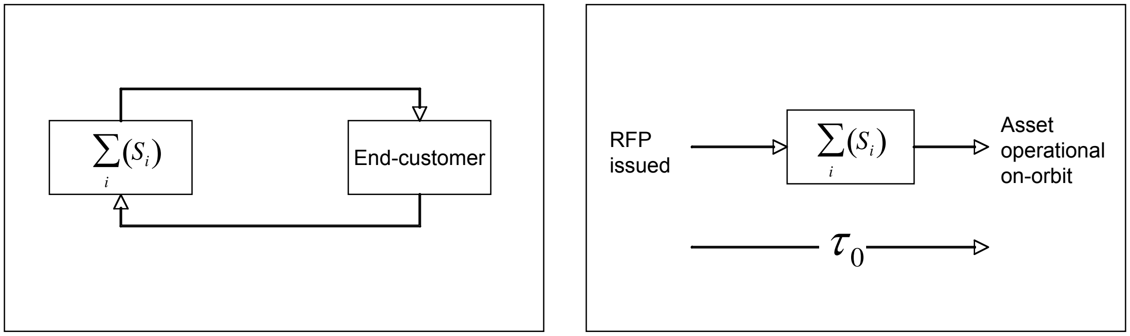
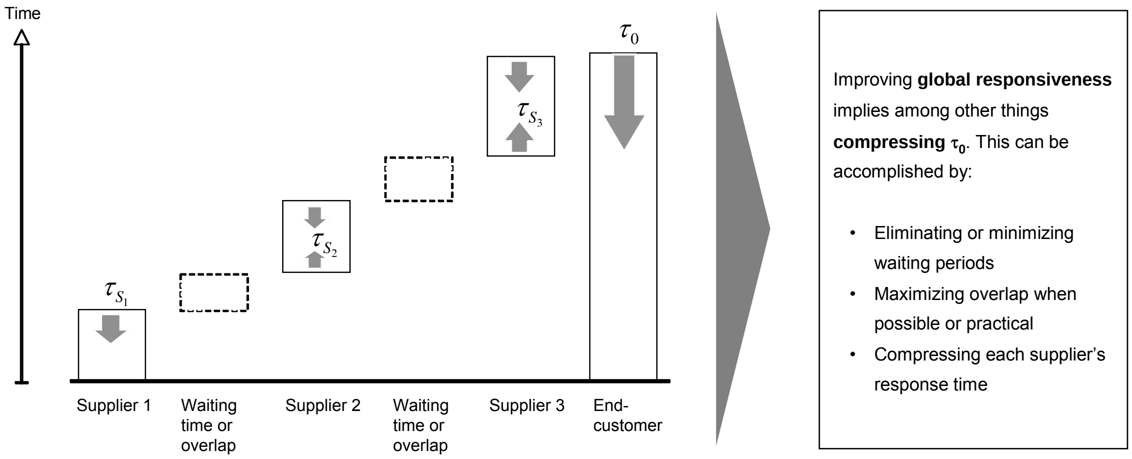


Figure 5. Global responsiveness, end-customer, and block diagram

Conceptually, compressing τ_0, and consequently improving global responsiveness, can be achieved by three different types of actions: (1) eliminating bottlenecks in the value-chain and minimizing waiting periods, (2) maximizing overlap, to the degree possible, between different streams of activities at different suppliers, and (3) compressing the “response time” of each supplier. In practice, in order to identify levers for improving responsiveness, lower levels of responsiveness—the constituents or components of this global responsiveness—must be defined, to identify areas where practical improvement actions can be taken. Two additional levels are introduced to this effect, local stakeholder responsiveness, and interactive or inter-stakeholder responsiveness.



Improving **global responsiveness** implies among other things **compressing τ_0**. This can be accomplished by:

- Eliminating or minimizing waiting periods
- Maximizing overlap when possible or practical
- Compressing each supplier's response time

Figure 6. Conceptual improvement of global responsiveness

2.3.2 Local stakeholder responsiveness

In addition to the global responsiveness, responsiveness can be defined at a local level in an industry value-chain, by local customers instead of the "end-customer". For example, in Figure 4, the local responsiveness of S_{11} is seen from the perspective of its customer, S_1, and is related to the total time τ_{S11} elapsed from the instance when S_1 formalizes its needs with respect to a given supplier, here S_{11}, to the time when S_{11} delivers the required product and/or service and fulfills its customer's needs. Improving local responsiveness implies among other things reducing or compressing this total time τ_{S11}.

2.3.3 Interactive or inter-stakeholder responsiveness

Each stakeholder, by improving its own local responsiveness (τ_{Si}), contributes to improving the responsiveness of its own customer(s), and ultimately the global responsiveness. However, the responsiveness of a local customer is not only dependent upon and determined by the responsiveness of its suppliers, but also by how well (or efficiently) the customer interacts and works with its suppliers. For example in Figure 4, the responsiveness of S_{22} is not only determined by the intrinsic responsiveness of its suppliers, S_{221} and S_{222}, but also by the time-efficiency of the interaction between S_{22} and its two suppliers. This can be referred to as "interactive" or "inter-stakeholder responsiveness" and characterizes the time-efficiency of the interaction between any two stakeholders in an industry value-chain. The time constant associated with this interactive responsiveness is noted as τ_{inter_resp}. For example, a customer that can finalize procurement agreements with its suppliers in a few weeks has a better interactive responsiveness than one requiring several months to set up such agreements.

2.3.4 Formalization

The time constant associated with the responsiveness of a local stakeholder, τ_{LS}, can be expressed as a function of the response times of all its suppliers S_i (i = 1 to n) plus the interactive responsiveness and the intrinsic responsiveness of the local stakeholder as shown in the symbolic representation of Eq. 2.1:

$$\tau_{LS} = f\left(\tau_{S_1}; \tau_{S_2}; \ldots; \tau_{S_n};\ overlaps\right) + \tau_{inter\_resp} + \tau_{intrinsic(LS)} \tag{2.1}$$

$\tau_{intrinsic(LS)}$ is a time component of τ_{LS} that captures the speed and efficiency by which a local stakeholder (LS) can address its own customer's needs irrespective of, or following its suppliers' responsiveness and the interactive responsiveness, as shown in Eq. 2.1. $\tau_{intrinsic(LS)}$ can be termed the local customer's "self-responsiveness," and is function of the internal technical skills within the company as well as the managerial skills and organizational structure that facilitate or hamper lean operations and decision-making. The functional dependence of τ_{LS} on various parameters (Eq. 2.1) is now discussed.

2.4 Schedule compressibility and responsiveness maps

Improving space responsiveness requires identifying the activities a_i contributing to the overall development and readiness of the system, and assessing the extent to which the duration of each activity τ_{ai} can be reduced. These tasks can be performed via the time compressibility metric along with the responsiveness maps, which are presented next.

2.4.1 Schedule compressibility

As the time dimension of responsiveness is related to τ_0 for the global responsiveness, and τ_{Si} for the local stakeholder responsiveness, improving a company's or an industry's responsiveness implies among other things compressing these time scales. By analogy with the notion of compressibility in fluid dynamics, a time compressibility metric can be defined as the relative change in τ_0 per unit increase in effort or resources, or symbolically:

$$\beta \equiv -\frac{1}{\tau_0}\frac{\partial \tau_0}{\partial r}$$

or (2.2)

$$\beta \equiv -\frac{1}{\tau_0}\frac{\Delta \tau_0}{\Delta r}$$

When expressed for every activity a_i in the space industry that follows the issuance of an RFP for a new or modified on-orbit capability, this time compressibility metric can help the analyst and decision-maker to think explicitly about the functional dependence of the schedule for developing a spacecraft on the resources that can be allocated to the various activities in the development and manufacturing process. This metric need not be considered with the analytic rigidity that Eq. 2.2 may suggest, but can be assessed qualitatively (e.g., low, medium, high) through the solicitation of experts' opinion and judgment of engineers and program managers.

2.4.2 Responsiveness maps

Given all the activities $\{a_{i,j} \mid j = 1 \text{ to } m\}$ performed by a given space industry stakeholder, S_i, to satisfy its customer's needs, and $\tau_{ai,j}$ the duration of each activity, a "**responsiveness map**" can be constructed as follows (Figure **7**): the x-axis is constituted by the compressibility of each activity undertaken by stakeholder S_i, and the y-axis is the normalized duration of each activity with respect to the total response time of the stakeholder. Each activity undertaken by S_i is then placed on this responsiveness map.

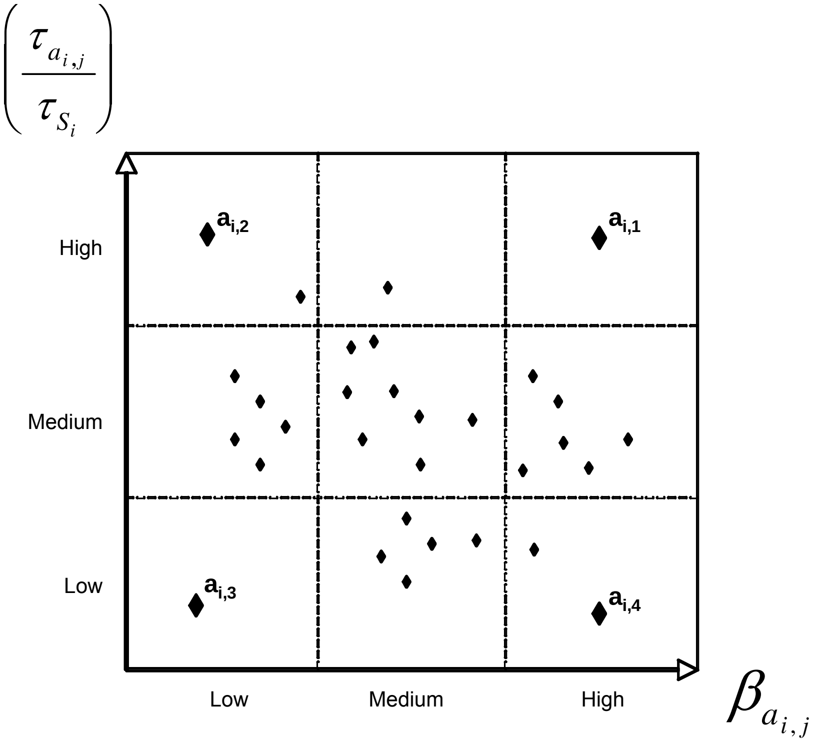


Figure 7. Responsiveness map for a given stakeholder Si

Figure 7 can be interpreted as follows:

1) The **upper-right corner** contains activities that are highly compressible (e.g., $a_{i,1}$), that is with limited additional effort or resources (people and/or money) their time to completion can be dramatically reduced. Furthermore, these activities are major contributors to the total response time of the stakeholder, i.e., they constitute important bottlenecks. Therefore, these activities in the upper-right corner should be tackled first in a responsiveness improvement effort.
2) The **upper-left corner** of Figure 7 contains activities that cannot be easily compressed even if they were allocated additional resources, yet these activities constitute important bottlenecks for the company (e.g., $a_{i,2}$). In other words, the

time reduction sought in tackling these activities are more difficult to obtain than in streamlining the activities in the upper-right corner.

3) The **lower-left corner** contains activities that are neither easily compressible nor do they constitute bottlenecks in the overall workflow to deliver a product or service (e.g., $a_{i,3}$).
4) The **lower-right corner** contains activities that are easily compressible but that do not constitute bottlenecks in the overall workflow to deliver a product or service (e.g., $a_{i,4}$).

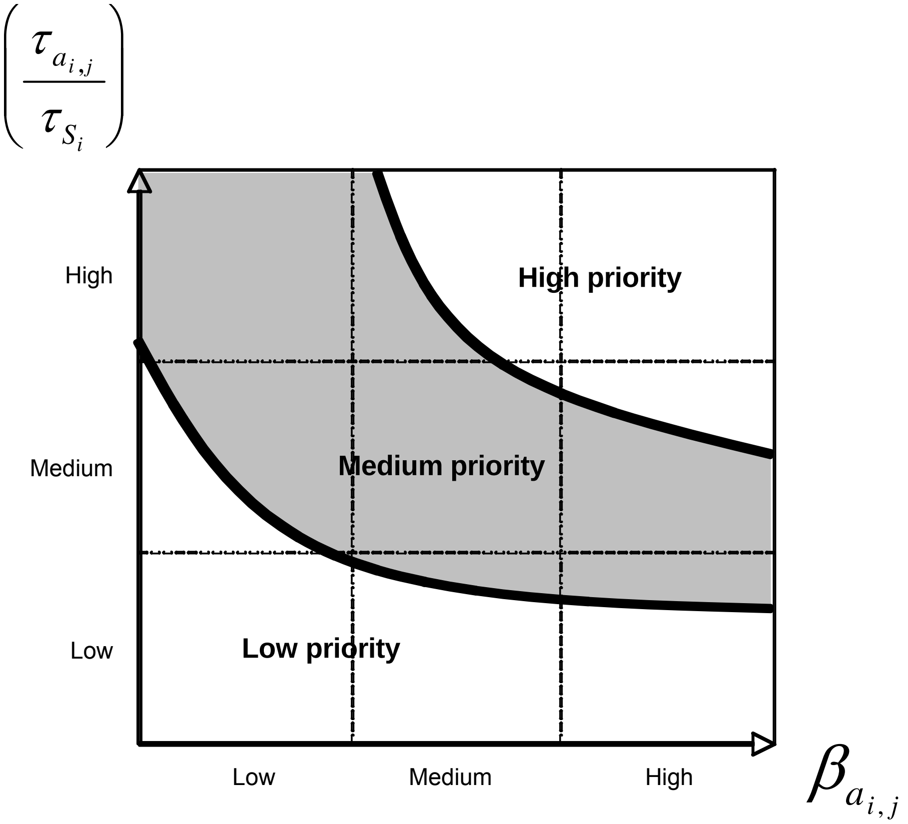


Figure 8. Responsiveness map and prioritization of improvement efforts

Responsiveness maps can be developed for every stakeholder in the space industry, and multiple layers or levels of detail can be included on these maps. Once such maps are developed, a company can prioritize its responsiveness improvement efforts by tackling activities in the higher priority sectors as shown in Figure 8.

The time compressibility metric, as defined in Eq. 2.2, captures one important functional dependence of the development schedule of a complex system, namely the relationship between schedule and resources. The development schedule however, and more generally τ_{LS} and τ_0, are not only dependent on resources, but also on other "structural" considerations: for example, a change in development process, a modification of program reviews, a change in the architecture of the system under development, or a change in the procurement practices can significantly impact τ_{LS} and τ_0, by modifying or eliminating some of the activities $\{a_{i,j} \mid j = 1 \text{ to } m\}$. Responsiveness can therefore be improved by acting on various "levers of responsiveness", which are presented next.

2.5 Levers of responsiveness

In a broad sense, improving the responsiveness of the space industry can be achieved by improving each or any local stakeholder's responsiveness (i.e., having more responsive satellite manufacturers, launch providers, and/or launch ranges, and in general more responsive "suppliers"). It is important to note however that the objective of compressing delivery times and improving space responsiveness is quite ambitious, given that many past and current space programs have experienced and continue to experience significant schedule slippage, as discussed in section 1.1. When exploring ways to improve responsiveness, it is therefore essential to recognize the dual nature of this problem: the prevention of responsiveness deterioration or schedule slippage as one side of the coin, and the schedule compression as the other side of the coin.

These two complementary tasks can be achieved by acting on **levers of responsiveness**[†] described next. Figure 9 provides a graphical summary of various levers of responsiveness presented in the following section, and their impact on the time constant τ_0, which is indicative of the global space industry's responsiveness.

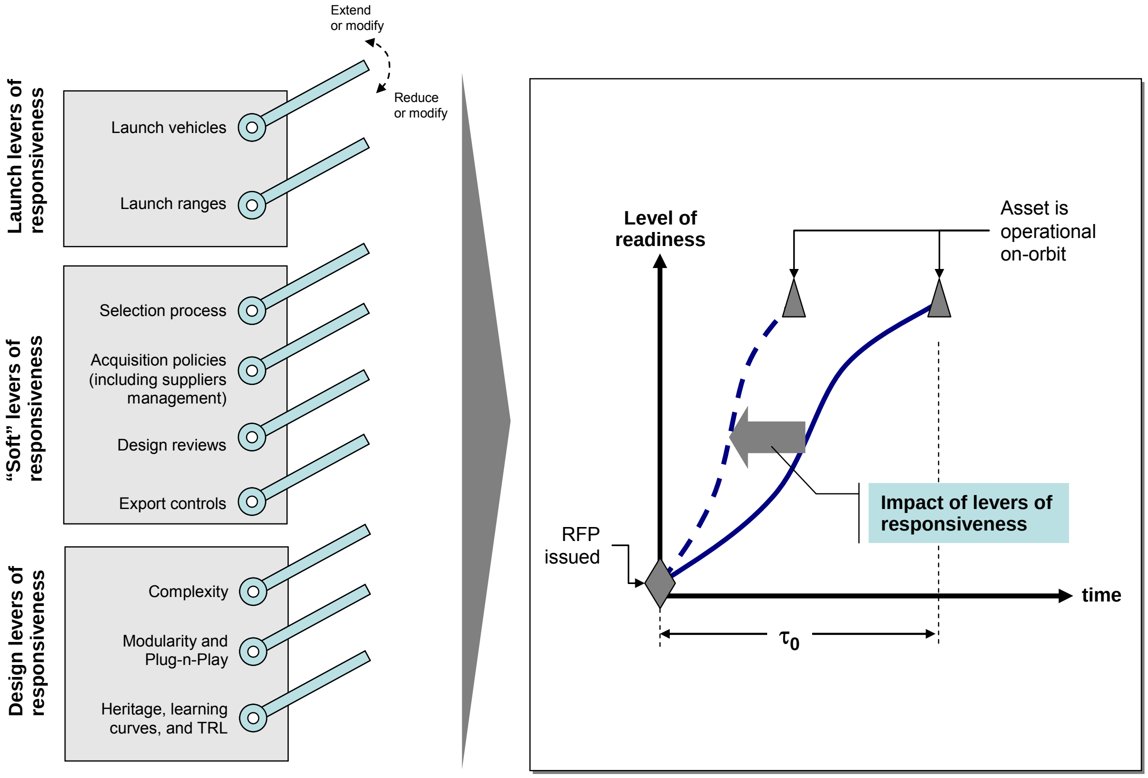


Figure 9. Summary of levers of responsiveness and their impact (when pulled in the "right" direction)

[†] Whether these levers should be pulled—and to what extent—or not is dependent upon numerous considerations and should be part of larger analyses and trade-offs performed during the design.

2.5.1 The launch levers of responsiveness: launch vehicles and launch ranges

2.5.1.1 Launch vehicles

Launch vehicles are key-enablers of the global space industry's responsiveness. At present, it typically takes several months from the time a spacecraft is shipped from the manufacturer's premise to the launch facility, to the time when it is placed on orbit. This duration is increasingly viewed as an objectionable lack of responsiveness, both for commercial and (especially) military customers. In response to this problem, new launch vehicles aiming at meeting the Operationally Responsive Space (ORS) requirements are developed to reduce the launch response time to a few days [11]. One proposed solution requires having launch vehicle parts available "off-the-shelf," so that launchers are built-to-inventory. Such a new approach implies new constraints, among which is the use of propellants capable of being stored at ambient temperatures. [12].

One major problem underlying launch responsiveness, or lack of it, resides in what is referred to in the Operations Research literature as the **build-to-order** versus the **build-to-inventory** production approaches [13]. Launch vehicles today are effectively built-to-order, that is, they are built for a specific mission/spacecraft and after a confirmed order–with all the financial guarantees–for the vehicle has been placed [14]; the build-to-order approach is sometimes referred to as "pull" production system in which the market effectively "pulls" the products from the manufacturer. By contrast, the build-to-inventory is a "push" production approach in which products are manufactured (and sent to the "inventory") not in response to confirmed orders, but in the hope that "pushing" said products onto the marketplace will result in them being purchased. It is easy to conceive of hybrid production approaches that lie between these two ends of the spectrum (BTO and BTI) and for which 1) products are built in part to order, and in part to inventory, 2) products are built to (credible) sales forecast, 3) products are built with varying degrees of commitments from the customers (shy of firm orders). These various productions approaches differ in their consequences on responsiveness as well as in their economic and risk implications, due to the following considerations (summarized in Figure 10):

1. Launch vehicles are highly complex and costly artifacts. The design of launch vehicles is driven by and matches the present day dominant design of spacecraft as large monoliths.
2. Given the high cost of a launch vehicle and the low volume nature of the launch business, launch providers cannot afford the financial risks that come with the build-to-inventory production approach, or the significant inventory holding costs associated with this production approach. The build-to-order approach therefore is both a lower risk and cost approach to the launch providers than the build-to-inventory.
3. From a customer's perspective however, the build-to-order of launch vehicles, unlike the build-to-inventory, is a non-responsive approach and results in significant delays before a needed capability is placed on-orbit. Launch responsiveness, as seen from the end-customer's perspective (e.g., the U.S. Air Force), is therefore traded against lower financial risks and inventory costs by the launch providers.

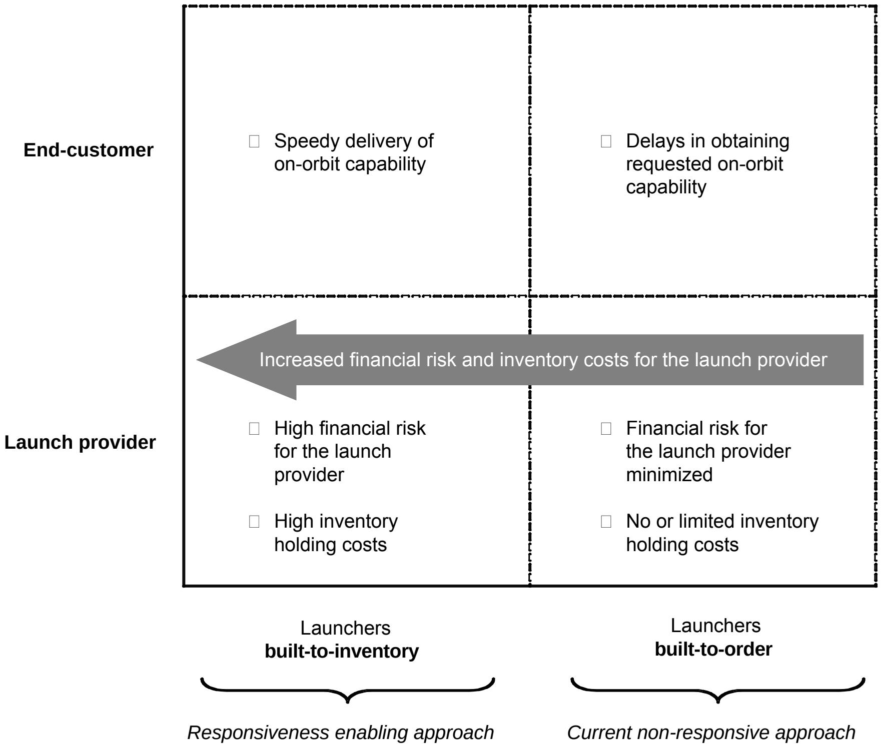


Figure 10. Responsiveness and implications of BTO and BTI to launch providers and end-customers.

Enticing the launch providers to switch from a BTO to BTI, and hence towards a more responsive production approach, will succeed only when credible economic solutions are found to: 1) distribute the financial risks between the launch providers and the end-customers; 2) have the latter share in the inventory holding costs associated with the build-to-inventory approach.

Another hypothetical solution for the switch from BTO to BTI is to dramatically lower the cost of launch vehicles. This can only happen if the current dominant architecture of spacecraft (large monolith) is significantly disrupted and a new spacecraft design paradigm emerges and proves competitive, such as powerful micro-satellites or fractionated spacecraft [15].

2.5.1.2 Launch ranges

Just like airports have a limited capacity to handle air traffic, so do launch ranges have a limited launch turnover rate. Saturation of the launch range capacity can generate an important “bottleneck” representing a challenge for the responsiveness of the space industry, as the current number of launch ranges around the world is not sufficient to satisfy the demand without generating waiting periods. In addition, most ranges are government-owned, and function under significant restrictions that often result in delays of the order of months in their operations. As a result, several initiatives have recently emerged to build private launch ranges that would allow leaner operations and would “un-choke” the current flow of demand in launches. For example, the Mojave Spaceport became the first facility to be certified as a spaceport by the U.S Federal Aviation Administration (FAA) in 2004, and allowed the flight of X-Prize’s winner SpaceShipOne. Similarly, Spaceport America, built in New Mexico in 2006, experienced its first successful launch of a SpaceLoft XL rocket in April 2007.

Since spaceports are typically built around specific vehicle designs, any required modification to accommodate new vehicle architecture can be time-consuming, i.e., “on the order of several years” [16]. New practices in the design of launch ranges are therefore sought to make spaceports compatible with the requirements of Responsive Space, and move towards airport-like operations. These practices include for example a reduction of complexity by reducing the number of ground interfaces with the launch vehicle, as well as a standardization of these interfaces [17]. Furthermore, vehicle and payload characteristics (e.g., propellants used, geometry of launch vehicles, on-site integration of components, special payload services) are thought to have an influence on the responsiveness of the launch range [18]. These design interactions between the vehicle and payload with the launch range can be seen as impacting the "interactive responsiveness" as conceptualized in Eq. 2.1, since in that case the responsiveness is jointly controlled by the launch vehicles and the launch ranges. Finally, new spaceport and range technologies offer promising opportunities to reduce turnaround times, reorganize the scheduling of range assets more efficiently, and increase the availability of the launch windows [16].

2.5.2 The soft levers of space responsiveness

Recent initiatives to meet the goals of Operationally Responsive Space have mostly focused on two categories of levers of responsiveness, launch-centric and design-centric levers of responsiveness (presented in section 2.5.3). Practical achievements that illustrate this effort include for example the TacSat series of satellites that combine the use of small, modular satellites with rapid and low cost launch vehicles [19]. However, efforts to improve space responsiveness ought not focus solely on the technical and operational characteristics of the artifacts created by the space industry, but should also address the legal, organizational, and managerial aspects of "doing business" in this industry. These **"soft" levers of responsiveness** include the selection process of competing proposals in response to an RFP, the design reviews during the development process, and the acquisition policies of space assets (this last point is relevant in the particular case of military acquisition).

2.5.2.1 Selection process

The selection process of proposals in response to an RFP can significantly delay the start of the development of a space program, thus jeopardizing its responsiveness. In the case of NASA's Discovery missions, this selection process can take up to 2 years from the "development of a draft [Announcement of Opportunity] AO until the start of mission formulation" [20]. In a Federal acquisition context for example, the selection process of space assets should not only emphasize fairness and accountability, but also explicitly timeliness. A reduction in time of the selection process from two years to say a few months therefore represents an important lever for space responsiveness.

2.5.2.2 Design reviews

Spacecraft are developed according to the traditional stage-gate development model with multiple design reviews that punctuate the development process. Repeated and extensive design reviews can significantly stretch the development schedule of a spacecraft [21] and thus degrade responsiveness. In an environment where responsiveness is increasingly important, it is worth **carefully** exploring other more expeditious or less frequent reviews and controls approaches. Reviews support transparency and minimize technical and programmatic risks between customers and suppliers—for example between an end-customer, e.g., a satellite operator and a satellite manufacturer. Minimizing the frequency or limiting the extent of the design reviews may have some benefits in terms of responsiveness. However, it should be recognized that this potential lever on responsiveness, which acts on the interactive responsiveness ($\tau_{inter\_resp\ term}$ in Eq. 2.1), comes at a cost of increased programmatic risk and less transparency between the end-customer and the satellite manufacturer.

2.5.2.3 Acquisition policies

Recent studies by the U.S. Government Accountability Office (GAO), as well as the report of the Defense Science Board/Air Force Scientific Advisory Board Joint Task Force on Acquisition of National Security Space Programs (also known as the “Young Panel report” [6]) are consistent in their findings that the DOD space acquisition policies, despite recent reforms, are failing, with the result that many space programs have experienced cost growth sometimes exceeding 100-percent, and significant schedule delays, in some cases as much as 6 years [3,22].

Better practices in systems acquisition have thus been found to constitute effective levers of responsiveness, if not for compressing systems delivery times at least by helping programs stay on schedule. The following are some example of policy recommendations that can be conceived of as levers of responsiveness (the first two are related to the technology heritage lever discussed previously):

- Technology development should not be undertaken in an acquisition program [23,24]. The rationale for this recommendation is that technology development cannot be easily time-compressed and it is the most likely to cause schedule slippage. As a result, GAO recommends confining technology development to the research and development environment, which is more forgiving of schedule slippages than acquisition programs where responsiveness matters. One practical instantiation of this policy is GAO’s recommendation that acquisition programs not include technologies with a TRL lower than 6 or 7 in the development of a space system (see the “technology heritage” lever of responsiveness in section 2.5.3.3) [22,25].

- Stable definition of system requirements is critical to ensure space responsiveness, since frequent significant changes in these requirements often result in schedule delays [6,24].
- The number of officials and organizations involved in defining the requirements for space systems should be limited to avoid the proliferation of requirements [6,24] and sufficient authority should be given to program managers to make the necessary trade-offs between requirements, requirements growth, and responsiveness.

2.5.2.4 Export control laws and regulations

When a country exports some of its space technology and shares it with foreign entities, its national security as well as the competitiveness of its space industry are at a potential risk. Export control laws and regulations are established to monitor the type of technology and information that can be exported, in order to protect national security and commercial interests. Under such regulations, technology must undergo an administrative process punctuated by various reviews and approval requests before being exported. In the United States, almost every field of science and engineering is covered by the Export Administration Regulations (EAR), supervised by the U.S Department of Commerce, and/or the International Traffic in Arms Regulations (ITAR), supervised by the U.S Department of State. In 1999, non-military space technology, which had been handled by the Department of Commerce for several years, returned to the U.S Munitions List (USML) subject to the stricter ITAR control. A policy of this nature can have significant implications in terms of space responsiveness. In the case of the U.S space industry, this effect manifested itself in various ways:

- The more stringent reviews of space-related technology by the Department of State were found to be much more lengthy than when they were handled by the Department of Commerce (in roughly 17% of the cases treated by the Department of Commerce, the review time was greater than 60 days, whereas this proportion goes up to approximately 48% for cases treated by the Department of State [26]).
- Spacecraft is the commodity group for which permanent export licenses granted by the Department of State take the longest to process [27].
- The average time needed to approve Technical Assistance Agreements (TAA's), which are critical to international cooperation and marketing, has increased from 52 days in 2003 to 106 days in 2006 [28].
- International partners have also observed the increasing delays of space projects resulting from the application of ITAR [29].
- The time needed to obtain export licenses is hard to predict with confidence [30].

As export control laws and regulations have a significant impact on schedule of space systems (and as a result, on the competitiveness of the space industry), various steps can be taken to improve responsiveness in this area. These include:

- A clearer distinction between the truly military-sensitive technology and the more harmless commercial technology, both at the industry level (e.g., removing commercial satellites from the munitions list), and at the spacecraft level (e.g., distinguishing the sensitive components from the non-sensitive ones)
- A clarification of the role and authority of each administrative entity in granting export licenses (interactive responsiveness)

- Improving the efficiency of the entities which conduct the reviews and grant export licenses (self-responsiveness of each administrative entity).

2.5.3 Design and architecture levers

In addition to extra resources and to the launch and soft levers of responsiveness presented previously, the development and manufacturing schedule of a system also depends on the nature and characteristics of the system under development such as its complexity, heritage, and more generally its architecture.

2.5.3.1 Modularity, Plug-n-Play (PnP), and standardization of interfaces

The many definitions of modularity [31] derive from the notion of *module*. In product design, a module is a component or group of self-contained components that: 1) has well-defined interfaces to a platform, a system, and/or other modules; 2) provides a specific self-contained function within the system in which it is embedded [32]; 3) can be "removed (or interchanged) from a product non-destructively as a unit" [33]; 4) can be easily "plugged" into a system, and both its presence and the function it provides are directly recognized by the system and put to use accordingly. Modularity acts as a lever of responsiveness by operating at least on two levels:

- **System-level impact**: in an integral design (the "opposite" of modularity), components are tightly coupled, physically and functionally. Because of the lack of physical and functional separation, the system's development cycle is constrained to a large extent to be sequential, with limited or no possible overlap between different development phases. By contrast, decoupling of functions between different modules allows a certain degree of parallelism among the tasks performed during the development of a modular system [31]. Since modules are separate, providing specific and self-contained functions, they can be designed, assembled and tested separately and simultaneously, offering potential time-savings and thus responsiveness improvements. The total development time of a modular spacecraft can be symbolically expressed as in Equation 2.3:

$$\tau_{modular} = \tau_{design} + \tau_{assembly} + \tau_{testing} - \sum_{i \neq j} \tau_{overlap(a_i\,;\,a_j)} \tag{2.3}$$

The system-level improvements of responsiveness enabled by modularity are represented by a negative term that subtracts the overlaps between various activities in the development cycle of a modular system design.

- **Module-level impact:**

  Modularity is sometimes designated in the literature as a “plug-and-play” (PnP) approach. Interfaces between modules (and/or between modules and platform) need to be designed in advance, and modules must comply with the standards pre-defined in order to be connected through these interfaces to the platform or overall system. Among the benefits presented by this upfront investment in modularity and standardization of interfaces, the re-use of similar modules is intuitively associated with a reduction in product development time [33]. In the case of spacecraft, schedule reduction or responsiveness improvements can result from the adoption of modular designs, since certain tasks performed once on a given module need not be performed again when a similar module is being built. This effect is particularly noticeable for the design and qualification phases. For example, once a module has been tested and (space-)qualified, its subsequent versions will require limited amount of additional testing before it can be integrated into a new system (see [34] for the modeling of cost savings resulting from modularity in spacecraft design). Several stakeholders in the space industry, including the U.S. Air Force Research Laboratory, have recently embarked on the development of technology infrastructure and the formulation of standards to support spacecraft PnP [35, 36, 37] and proposed modular designs of spacecraft subsystems and payloads [38] in support of improving space responsiveness.

2.5.3.2 Complexity

Engineers and program managers are interested in design complexity, its measures, and implications on schedule, cost, and risk among other things. In general, design complexity is indicative of: 1) the total number of subsystems or components used in an engineering system; 2) the number of different kinds of subsystems used (i.e., degree of heterogeneity); 3) the number of interfaces and connections between these subsystems (i.e., organizational complexity). Detailed discussions of complexity and its measures can be found in [39,40,41]. It is commonly accepted that design complexity dramatically impacts the development and assembly time of a product [42,43].

In the case of spacecraft, complexity influences all the parameters identified in Eq. 2.1, (in which the local stakeholder (LS) is the spacecraft manufacturer) in at least three ways:

- *Component-centric*: a decrease in system complexity can be reflected by a reduction of the number (and diversity) of subsystems and payload instruments to be developed, as well as their connections and interfaces. As a consequence, lower complexity results in shorter design and development times for the different “parts” of a spacecraft.

- *System-centric:* a decrease in spacecraft complexity reduces the amount of time required to integrate and test the whole spacecraft.
- *Organizational:* a reduction in spacecraft complexity is likely to result in fewer stakeholders and suppliers involved in delivering “parts” to the spacecraft. Fewer suppliers are likely easier to be managed than scores of them, thus reduced spacecraft complexity has also the potential to improve the interactive responsiveness.

For example, the number of instruments on-board a spacecraft is a proxy for the spacecraft size and is one possible indicator of the system’s complexity. As a design choice, this number of instruments carried on board will influence a space program’s schedule and can therefore significantly impact responsiveness. When other factors contributing to complexity (such as design lifetime, power, or propulsion type) are taken into account, more complex missions tend also to take longer to be developed [44].

2.5.3.3 Heritage, learning curve, and Technology Readiness Level (TRL)

The three terms, *heritage*, *learning curve*, and *TRL*, cover closely related concepts in engineering design. The idea of improvement in cost resulting from repetitive tasks was formalized by T.P. Wright [45] and its adaptation for development and assembly times [46] can be written as follows:

$$T_{n^{th}} = T_1 \times n^b \tag{2.4}$$

and

$$b \equiv \frac{\ln(R/100)}{\ln(2)} < 0 \tag{2.5}$$

where $T_{n^{th}}$ is the development and assembly time of the n^{th} unit, T_1 the development and assembly time of the first unit, and R is referred to as the learning rate. The application of Eq. 2.4, and the schedule advantages—or time compressibility—resulting from heritage and learning curve effects are illustrated in Figure 11, where the cumulative production time for n identical units is plotted with and without learning effects. In the case of commercial communication satellites, the production of a large number of identical units and the resulting time savings may explain (at least partly) their higher responsiveness compared to that of military and scientific missions, as observed previously on Figure 3. *Heritage*, as shown in Figure 11, is the "depth of the past" or the amount of experience in producing identical units (n), whereas what is traditionally referred to as the learning curve, or learning rate, R is another parameter that determines the improvements (in terms of production time or cost) between two identical and consecutive units produced. (The cost analog of this model (Eq. 2.4) is sometimes written as follows: $C_{n^{th}} = C_{TFU} \times n^b$. For this model, "the learning rate (R) for the space and aerospace industry is such that, on average, the n^{th} unit will cost between 87% and 96% of the previous unit" [47]).

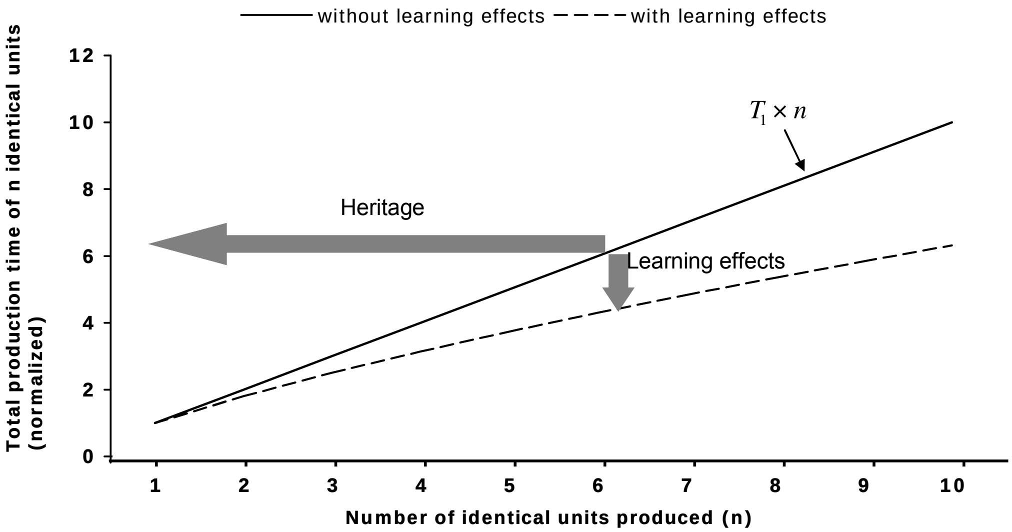


Figure 11. Heritage and learning effects for R = 80% (illustrative)

In addition to *heritage* and *learning curves*, the aerospace community has also developed and widely adopted the concept of *Technology Readiness Levels*, or TRL, introduced by NASA in the 1980s [48]. “TRL [is a] systematic metric/measurement that supports, 1) the assessments of the maturity of a particular technology, and, 2) the consistent comparison of maturity between different types of technology” [49]. This metric is organized on a scale of nine levels corresponding to key stages of development of a given technology, as briefly described in Table 1. TRL has been traditionally used to assess the development (and cost) risk of a spacecraft. For example, whether only in-flight proven technologies should be admitted in response to an RFP, or not, has potential implications on the design and development schedule of a spacecraft. The lack of technology maturity or low TRL, sometimes described in the literature as technology uncertainty, is often associated with schedule risk, albeit qualitatively. Browning [50] defines schedule risk as the “*uncertainty* in the ability of a project to develop an acceptable design […] *within a span of time*, and the consequences thereof.” The author also defines technology risk as the "*uncertainty* in capability of technology to provide performance benefits (within cost and/or *schedule expectations*), and the consequences thereof."

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

By their definitions alone, these concepts suggest a close relationship between technology uncertainty and schedule risk. In fact, in a study conducted by Gupta and Wilemon [51] of large technology-based firms, "about 58% of the interviewees cited technological uncertainties as a major reason for delays.” The link between technology uncertainty and technology maturity is intuitive: the more mature a technology is, the more knowledge is available concerning its development, manufacturing, and mode(s) of operation. This, in turn, provides a higher confidence level that the mission requirements will be met. As a result, technology uncertainty in the project is reduced. Therefore, maturing technology is critical to completing a program on schedule and within budget.

Low TRL of the space system/payload under development has been repeatedly identified by the U.S Government Accountability Office as an important culprit associated with schedule slippage [2,22,25,52,53]. Indeed, as the low-TRL world (research environment, or S&T in government parlance) and the high-TRL world (e.g, development and production) are significantly different and do not always interact seamlessly, it is hard to predict how smooth this maturation process will be, and more importantly, how much time it will take to bring a low TRL technology (e.g., TRL = 4) to a comfortable level of maturity (e.g., TRL = 8). This issue is sometimes referred as the **TRL gap** and is described by George and Powers as “the problem of efficiently transitioning a new technology from concept to viable product in the **shortest possible time** and at the least cost” [54].

TRL, learning curves and heritage, bundled under the single heading of “technology heritage”, have therefore significant implications on the design of space systems in general and are likely to impact all the parameters identified in Eq. 2.1, which determine the local and global responsiveness. In short, the use of higher technology heritage in space programs is likely to result in faster delivery times and hence improved responsiveness. The following section further investigates the impact of TRL as a design-centric lever of responsiveness and explores its influence on schedule slippage.

2.6 TRL, schedule slippage and responsiveness: an example of univariate analysis

To analyze quantitatively the impact of design levers on responsiveness and schedule slippage, one preliminary step consists in looking at the influence of each design attribute on schedule, treated independently. In the following, an example of univariate analysis of schedule slippage is provided, by considering TRL as the independent variable and using it as a proxy for technology maturity (or lack of). Schedule slippage is thus considered a random variable, or more precisely, a random vector or an indexed family of random variables with TRL as the index. This section proposes to characterize through data analysis and modeling the central tendency and dispersion of this random variable as a function of TRL.

2.6.1 Data Description

Paradoxically, despite the fact that technology readiness level is a central theme in feasibility studies of system design (spacecraft and other), limited TRL data is available to the technical community for analysis—unlike other parameters such as system cost for example for which quantitative data and a number of (cost) models exist and are widely available. In some cases, when TRL is discussed in the technical literature, qualitative maturity levels (“Low/Medium/High”) are employed.

For the purpose of this analysis, programmatic data from 28 NASA programs was considered. Most of these programs considered here are unmanned, and include Earth science missions and interplanetary probes. Lee and Thomas [55] used this data to construct probability-based models for the cost growth of NASA's programs. Details about this data can be found in Ref. 55. This section focuses instead on schedule slippage and is concerned with three parameters from the data set:

1. TRL at start of program
2. Initial schedule Duration Estimate (IDE)
3. Final Total schedule Duration (FTD)

The Relative Schedule Slippage (RSS) is defined here as the percentage schedule growth given the initial schedule estimate:

$$RSS = \frac{(FTD - IDE)}{IDE} \cdot 100 \tag{2.6}$$

Recall that the objective of this section is to quantify how much schedule risk/slippage is associated with different levels of technology maturity or TRL. Given this objective, a regression analysis is performed on the data and the relationship between TRL and RSS is investigated. Both the central tendencies and the dispersion of RSS are analyzed as a function of TRL and the results are related to schedule risk and slippage. The details are further discussed in section 2.6.2.

Before proceeding, a subtlety concerning the TRL data should be addressed:

TRLs usually define the maturity of a given technology, and by extension, a TRL value is commonly assigned to a component characterized by one single technology. However, to extend the notion of technology maturity to an entire program, an average TRL value for a complex system must be defined. Lee and Thomas [55] calculated a weighted average of TRL for each program (WTRL), by taking the "TRL of each component multiplied by their corresponding percent of the allocated cost against the entire program's cost" as defined in Eq. 2.7.

$$WTRL_{program} = \sum_{components\, c_i} w_i \cdot TRL_{c_i} \qquad \text{where } w_i = \frac{cost_i}{cost_{program}} \tag{2.7}$$

$$system - TRL = \lfloor WTRL_{program} \rfloor = \max\left\{ n \in \mathrm{N} \,|\, \mathrm{n} \leq WTRL_{program} \right\} \tag{2.8}$$

For example, a complex system such as the Hubble Space Telescope is first broken down into subsystems (e.g., attitude control), which are then decomposed into components (e.g., control moment gyros)[‡]. The TRL of each component is then considered to regressively define the WTRL. This study used the WTRL as a preliminary basis for the "average system-TRL" whose influence on schedule slippage was investigated. The WTRL is proportional to the amount of resources spent for each component. Components with a small w_i are either of minor importance in the design, or their TRL is already sufficiently high to limit the allocated cost for their development and implementation. In both cases, it is reasonable to assume that such components will not critically impact the advancement of the schedule, which justifies the use of the WTRL for this schedule analysis. However, this WTRL calculation results in a value with decimal digits. Such a

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[‡] D. Thomas, personal communication, August 2007.

degree of precision was not relevant for this study. To obtain the average system-TRL (hereafter often simply referred to as "TRL"), the final step consisted in rounding down to the next integer by applying the floor function to the WTRL as shown in Equation (2.8). Here again, when considering components requiring a large resource investment, it is contended that those with the lowest TRLs drive the schedule delays, as they represent the "slowest links" of the maturation chain. For example, consider a program whose WTRL is 4.62. If it involves components with TRL 5 or 6, it also involves components with integer values of TRL less or equal than 4. First, the WTRL of 4.62 gives a good indicator of the "average TRL" of the entire system. Then, considering that components with low TRL (e.g., TRL = 4) have a bigger impact on schedule slippage than components with TRL 5, the integer value, that is TRL = 4 was retained.[§]

2.6.2 Modeling Schedule Slippage

For each of the 28 NASA programs in the data set, the doublet (TRL; RSS) where the TRL consists of the integer values discussed in the previous section is plotted and analyzed. The TRLs in the data set range from 4 to 8. The relative schedule slippage is considered a random variable—more precisely, a random vector or an indexed family of random variables with TRL as the index. In the following, both the central tendency and the dispersion of this random variable is analyzed and modeled as a function of the independent variable in this study, namely TRL.

[§] Following these logics, one could argue that the minimum of all the components' TRLs could be directly used in place of the WTRL. However, it is important to capture first the relative importance of every component in terms of the amount of resources spent. The WTRL provides this function.

2.6.2.1 *Mean relative schedule slippage*

The central tendency of RSS is captured by its mean or average value, which for a given TRL is defined as follows:

$$\langle RSS \rangle_j = \sum_{i=1}^{n} \frac{RSS_i}{n} \bigg|_{TRL=j} \tag{2.9}$$

Figure 12 shows the mean RSS for each TRL. For example, for a TRL = 4 at start of the program, Figure 12 shows that an average 78% schedule slippage has been observed in all 28 programs considered—in other words, programs' schedules have been consistently underestimated by 78% when the TRL at start of the program was 4 (this is low maturity technology in the context of a space acquisition program). Similarly, when TRL at start of the program was 7, Figure 12 shows a mean RSS of 19%.

More generally, Figure 12 shows a monotonically decreasing average RSS as a function of TRL. This result can be interpreted as follows: the quality of the initial schedule estimate (IDE) at start of the program improves (i.e., is more accurate) as the technologies considered for the program are more mature. Conversely, the lower the maturity of the technology considered, the less the actual schedule or FTD can be predicted with accuracy (i.e., the bigger the error in the program's initial schedule estimate). While this result may be considered intuitive, Figure 12 provides an empirical confirmation of this intuition.

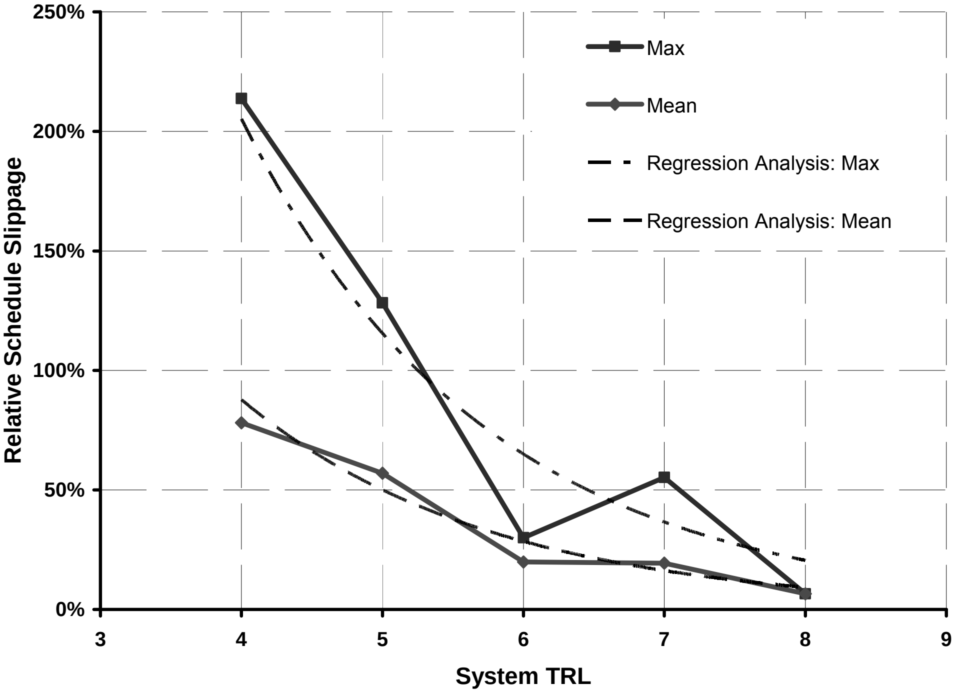

Figure 12. Relative Schedule Slippage (RSS) for 28 NASA programs (mean, max, and regression analysis) as a function of TRL.

To analytically reflect this trend, this work proposes to model the mean relative schedule slippage with a decreasing exponential function of TRL, and perform a regression analysis on the data set to fit the model parameters. Equation 2.10 represents the model structure:

$$\left\langle \overline{\mathrm{RSS}} \right\rangle = \alpha \cdot e^{-\lambda \cdot TRL} \tag{2.10}$$

This model structure was chosen both for its simplicity and conceptual relevance. A polynomial fit of order *n* >1 for example would be meaningless considering the small size of the sample, and the absence of a conceptual interpretation of the coefficients needed to ensure goodness-of-fit. More importantly, the needed function should 1) account for the reduction of the schedule slippage with higher TRLs, and 2) provide increasingly smaller increments in schedule slippage as TRL increases. Condition 2 can be stated mathematically as follows: the absolute value of the derivative of the $\left\langle \overline{\mathrm{RSS}} \right\rangle$ with respect to TRL should be a decreasing function. This justified the choice of a decreasing exponential function.

Table 2 shows the results of the regression analysis using this model structure (Eq. 4). A comparison of the observed and modeled mean relative schedule slippage is provided in Table 3. The model of the mean relative schedule slippage, which consists of Eq. 2.10 and the value of its parameters in Table 2, is fairly accurate, as reflected by the coefficient of determination R^2, 94%, and by the error between the model output and the observed data (less than 10 percent).

Table 2. Model parameters for the average schedule slippage in this data set

Model parameter	Value
α	8.29
λ	0.56
R^2	0.94

The R^2 parameter[**] indicates that the variability in the mean relative schedule slippage is primarily accounted for by the TRL. However, due to the limited size of the sample (28 data points with an average of 6 points for each TRL), the R^2 value of this model, 94%, should be considered with caution and not interpreted beyond the fact it indicates an accurate model.

Table 3. Model accuracy: mean relative schedule slippage and TRL

TRL	Observed mean relative schedule slippage $\langle RSS \rangle_j$	Modeled mean relative schedule slippage $\langle \overline{RSS} \rangle_j$	Error
4	78%	88%	10%
5	57%	50%	7%
6	20%	29%	9%
7	19%	16%	3%
8	7%	9%	2%

Note that while no spacecraft with an average system-TRL of 9 was found in the original data set, the modeled RSS mean extrapolated for a system-TRL of 9 yields a value of 5.3%, suggesting that schedule slippage may still occur for the highest level of technology maturity. This tends to validate the influence of non-technical parameters (i.e., the "soft" levers of responsiveness discussed in section 2.5.2) on schedule slippage.

[**] If y_i are the values of the dependant variable considered, $\hat{y}_i$ the fitted values, and $\overline{y}$ the sample mean, the coefficient of determination is defined by $R^2 = \frac{\sum_i (\hat{y}_i - \overline{y})^2}{\sum_i (y_i - \overline{y})^2}$, and takes a value between 0 and 1.

2.6.2.2 Dispersion of the relative schedule slippage

In addition to the mean relative schedule slippage, the data allows us to model the envelope or range within which the relative schedule slippage falls for each TRL. The range of the relative schedule slippage is referred to as its dispersion. In the following, the range or envelope of RSS is modeled by the upper- and lower bound (UB, and LB respectively) values of RSS for each TRL level:

$$\begin{cases} UB_j = \max\left(RSS_i\right)\Big|_{TRL=j} \\ \\ LB_j = \min\left(RSS_i\right)\Big|_{TRL=j} \end{cases} \tag{2.11}$$

The envelope and dispersion of the data set are defined by Eq. 2.12:

$$\begin{cases} env\left(RSS\right) = \left\{UB_j ; LB_j\right\} \\ \\ Dispersion_j = UB_j - LB_j \end{cases} \quad \text{for } j = 4, 5, 6, 7, 8 \tag{2.12}$$

The lower-bound model (LB_j) is trivial and equal to zero for all TRLs. In other words, for each TRL, at least one data point was found in this sample for which the initial estimated schedule (IDE) almost matched the actual schedule (FTD), thus resulting in an RSS almost equal to zero[††]. Consequently, the upper-bound model is also a model of the data dispersion.

The upper-bound is modeled with a decreasing exponential as defined in Eq. 2.13:

$$\left\langle \overline{\mathrm{UB}} \right\rangle = \alpha' \cdot e^{-\lambda' \cdot TRL} \tag{2.13}$$

Figure 12 shows that the dispersion of RSS narrows down as TRL increases. This dispersion can be considered a proxy for the time uncertainty in the technology maturation process: the lower the TRL, the bigger the schedule uncertainty, that is, the less we can predict with accuracy the time it will take to complete a project. GAO [3] put it more forcefully:

> *"There is no way to estimate how long it would take to design, develop, and build a satellite system when critical technologies planned for that system are still in a relatively early stages of discovery and invention."*

These results provide additional nuance to, and quantification of, this statement by GAO. Table 4 shows the results of the regression analysis using this model structure (Eq. 2.13). This model of the dispersion of the relative schedule slippage is fairly accurate, as reflected by the coefficient of determination R^2 (83%). However, the same caveat regarding the R^2 parameter discussed previously (2.6.2.1) also applies in this case of the dispersion model.

[††] This was a surprising result for the low TRL (4 and 5). It can be assumed that for these exceptional cases a significant schedule margins was probably factored into the initial schedule estimate, although unfortunately the data provided here does not allow the verification of this assumption.

Table 4. Model parameters for the maximum schedule slippage in this data set

Model parameter	Value
α'	20.47
λ'	0.57
R^2	0.83

Beyond the schedule estimation errors reflected by the mean RSS model (Equation 2.10 and Table 2)—these may be due to a variety of factors including intrinsically flawed schedule estimation methods in use by the industry—the dispersion of the RSS data suggests the existence of other sources of discrepancies between FTD and IDE (i.e., other than TRL), specific to each space program (e.g., complexity of the system under development, experience of the program manager, funding delays, requirements creep, etc.).

The models presented previously constitute an example of a univariate analysis of schedule that can help gain a preliminary understanding of the impact of one design parameter on schedule (or design lever of responsiveness). Here, technology maturity was considered the independent variable, measured through an average or aggregate TRL of the spacecraft subsystems. It is however important to recall that the concept of technology maturity has its primary meaning when considered at the subsystem or single-instrument level. For that reason, the use of TRL beyond its initial domain of validity for the characterization of an entire system has been criticized [56,57,58,59]. To address the limitations of the TRL scale, other metrics have been proposed to assess various aspects of the readiness of a complex system. The next section now briefly reviews such metrics to identify whether they can serve as the basis for a framework for modeling spacecraft schedule and helping guide design decisions.

2.7 Other readiness metrics for complex engineering systems

2.7.1 Integrated Technology Index

Observing that "TRLs do not provide any insight into the uncertainty that may be expected in pursuing the further maturation of the technology in an R&D program", Mankins [60] proposed a new metric called R&D degree of difficulty (R&D^3) to complement the existing TRL metric. The purpose of the R&D^3 is to help quantify the perceived difficulty in achieving research and development objectives, and to help decide on the appropriate number of design options to consider concurrently to reach those objectives. Note that it does not directly help quantify the time needed to bring a system to completion. In an effort to address the "technology challenge" that characterizes a complex system, Mankins then proposed the Integrated Technology Index (ITI), defined as follows:

$$ITI = \frac{\sum_{subsystem\ \ technologies} (\Delta TRL * R\,\&\,D^3 * TNV)}{\text{number of technologies}} \tag{2.14}$$

where for each technology, ΔTRL represents the gap between the current TRL and the intended TRL, R&D^3 represents the R&D degree of difficulty, TNV represents the Technology Need Value (TNV) that reflects the level of criticality of that specific technology. A concept with low ITI presents low technological uncertainty and viceversa.. Mankins states that the Integrated Technology Index "compensates inherently for the differing levels of fidelity with which different advanced systems concepts may be defined (since the number of technologies normalizes the sum of the individual index values)". In other words, ITI attempts to account for the disparities in technology advancement within a complex system; however the potential resulting integration difficulties are only captured in an indirect manner through the normalization by the number of technologies. The Integration Readiness Levels (IRL) described next have been defined to more explicitly measure the integration maturity between technologies embedded in a complex system.

2.7.2 Integration Readiness Level (IRL)

Initially inspired from the Open Systems Interconnect (OSI) standard for network systems, the Integration Readiness Level (IRL) scale was proposed by Sauser et al. [61] to evaluate the integration maturity of a technology. Its latest formulation [59] with a 9-level structure resembles that of the TRL scale and is presented in Table 5.

Several comments regarding the IRL scale and its relevance to the work conducted in this thesis can be made:

- Sauser et al. [59] state that "IRL does not evaluate cost and schedule", and much of the added value of the IRL scale pertains to the management of technical risk (as illustrated by the failure examples of Mars Climate Orbiter, Ariane 5 and Hubble Space Telescope presented by the authors as correlated with low-IRL technologies) rather than programmatic risk.

- Due to its conceptual connections with the OSI model, the proposed IRL scale puts much emphasis on data/information exchange. The integration of instruments and subsystems into a whole spacecraft not only requires the verification that the data/information remains consistent from one technology to the rest of the spacecraft (which is the main orientation of the IRL scale), but also necessitates that the integrity of the entire system (e.g., from a mechanical, electromagnetic, thermal, etc. standpoint) is maintained when a technology is integrated. While this may be implied by IRL 7-IRL8, the actual integration and testing of the technologies constitutes an important phase of the spacecraft development that this thesis seeks to more explicitly capture.

- The IRL does in fact relate to a duplet of technologies (Technology 1, Technology 2) rather than one single technology. The authors recall that "it is to be used to assess integration maturity between two TRL assessed technologies". It is therefore not sufficient per se to evaluate the maturity of the integration of a technology with respect to its entire environmental system or spacecraft host. Recognizing this limitation, the authors have proposed another metric called System Readiness Level (SRL) that builds on the concepts of TRLs and IRLs and that are presented next.

Table 5. Summary of different Integration Readiness Levels [59]

IRL	Summary description
IRL 1	An interface between technologies has been identified with sufficient detail to allow characterization of the relationship
IRL 2	There is some level of specificity to characterize the interaction (i.e., ability to influence) between technologies through their interface.
IRL 3	There is compatibility (i.e., common language) between technologies to orderly and efficiently integrate and interact.
IRL 4	There is sufficient detail in the quality and assurance of the integration between technologies.
IRL 5	There is sufficient control between technologies necessary to establish, manage, and terminate the integration.
IRL 6	The integrating technologies can accept, translate, and structure information for its intended application.
IRL 7	The integration of technologies has been verified and validated and an acquisition/insertion decision can be made.
IRL 8	Actual integration completed and “mission qualified” through test and demonstration, in the system environment.
IRL 9	Integration is “mission proven” through successful mission operations

2.7.3 System Readiness Level (SRL)

Sauser et al. [57] proposed a metric to “assess the maturity of the entire system that is under development”, and adopted a formulation based on the existing TRL scale as well as the IRL metric previously described. For a given technology i, they define SRL_i as follows:

$$SRL_i = \sum_j IRL_{ij} TRL_j \tag{2.15}$$

with $IRL_{jj} = 1$ and $IRL_{ij} = 0$ when there is no integration between technology i and technology j. SRL_i attemps to quantify "the readiness level of a specific technology with respect to every other technology in the system while also accounting for the development state of each technology through the TRL" [57]. A composite SRL index can then be defined as a weighted average of the SRL_i for all the technologies included in the system to reflect the overall maturity of the entire system. Note that in this form, the composite SRL index would present the same limitations than the averaged system-TRL that was presented at the end of section 2.6. The authors then investigated the possible mapping between their SRL index and the different phases of the system engineering life cycle but warned that "the SRL for one system cannot be compared to the SRL of another system unless they are the same system". In other words, the SRL (in its current formulation) could prove useful to monitor the advancement of the readiness of one given system, but it does not allow a consistent comparison across systems (unlike the TRL scale).

2.8 Summary

This chapter provided a review and synthesis of the literature on responsive space and the challenge of keeping the development of space systems on schedule. A multi-disciplinary framework was provided for thinking about and addressing issues of space responsiveness. Also discussed were tools for identifying and prioritizing responsiveness-improvement efforts. The levers of responsiveness, or means for improving space responsiveness were presented, including spacecraft design and operational levers, launch levers, and "soft" levers of responsiveness. In response to the first research objectives, this chapter then focused on one design-centric lever of responsiveness, namely the

Technology Readiness Level. The preliminary univariate analysis of schedule as a function of average system-TRL suggested that the overall level of technology maturity characterizing a space system at the start of its development has significant implications on schedule slippage and schedule risk. However, the concept of TRL is meaningful at the subsystem or single-instrument level rather than at the system level. In addition, other design parameters have a potential influence on schedule (as reflected by the dispersion of the RSS), that can be combined with the impact of technology maturity. Finally, the last section of this chapter briefly reviewed some other readiness metrics that could support the formulation of a framework for the modeling of spacecraft schedule in relation with design parameters. The System Readiness Level (SRL) metric exhibited the same limitation than an average system-TRL and does not appear to translate into an elementary design parameter whose meaning remains consistent across various design options. At a more fundamental level, the IRL metric highlighted the significance of technology integration in the spacecraft development process, which was not explicitly reflected in the Integration Technology Index (ITI). Nevertheless, its formulation (between a duplet of technologies), its focus (information-centric) and its purpose (managing technical risk), do not adequately address the thesis' objective of developing a framework for modeling spacecraft schedule that should help inform design decisions that have programmatic implications.

The next chapter proposes a modeling framework of spacecraft schedule based on the concept of "spacecraft technology portfolio" that

1) addresses the limitation of an average system-TRL (or a composite SRL) by considering the full spectrum of technology maturities of the various instruments (or subsystems) in a spacecraft
2) explicitly captures the significance of the integration and testing phase of the entire space system.

Furthermore, this model is formulated in a stochastic fashion, in order to reflect the uncertainties associated with the technology maturation and system integration processes.

CHAPTER 3

SPACECRAFT TECHNOLOGY PORTFOLIO: STOCHASTIC MODELING AND IMPLICATIONS FOR RESPONSIVENESS AND SCHEDULE SLIPPAGE

> **"By the fourth grade, I graduated to an erector set
> and spent many happy hours constructing devices of unknown purpose
> where the main design criterion was to maximize the number of moving parts and overall size."**
>
> Steven Chu, American physicist, 1997 Nobel Prize Laureate in Physics.

3.1 Introduction

This chapter extends the analysis conducted in chapter 2 by increasing the resolution on the technology maturity and assigning a TRL to each of the subsystems or instruments considered for the spacecraft. Furthermore, various design parameters, other than TRL, can drive schedule and also be considered as "levers of responsiveness". For example, the size and/or complexity of a spacecraft (as discussed in section 2.5.3.2), 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 [62] 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, this chapter thus proposes to add a portfolio dimension to the 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). This chapter adapts 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, a spacecraft is conceived of 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.

This chapter is organized as follows. Section 3.2 provides a brief overview of the concept of portfolio as it has traditionally been implemented by successful companies and the relevance of this approach to spacecraft design and schedule analysis is shown in section

3.3. In section 3.4, the relationship between technology maturity and delivery schedule is modeled at a micro-level via the formulation of a probabilistic model of the Time-to-Delivery (TD_i) for each instrument of the spacecraft's "portfolio." Based on actual data, models for the Time-to-Integration of the spacecraft and for the Shipping time of the spacecraft are then developed as a function of the number of instruments. The development of the entire spacecraft is finally simulated via the execution of 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 chapter 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 $TD_{s/c}$, the notions of Mean-Time-To-Delivery (*MTTD*) of a spacecraft and its schedule delivery risk are introduced. Section 3.5 investigates 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, section 3.6 discusses the utility implications of varying the portfolio characteristics and time-horizons, and provides "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).

3.2 The notion 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 [63]. 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) [64,65]. 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" [66]. More recently, Cooper et al. proposed a formal definition of portfolio management [67]:

> "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 prospective projects. In fact, resource limitations that were overlooked during the selection process often explain project cancellation [68,69].

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 [64]. 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 [63] and Roussel et al. [66] **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"[70]. 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"[71].

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"[70].

Numerous methods have been proposed and extensively discussed in the literature on developing and managing an R&D portfolio. Archer and Ghasemzadeh [68] 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 [72]. 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. [66] 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 [73], Cooper et al. [67], Chen-Fu Chien [74], Linton et al. [75], Henriksen and Traynor [76], Martino [77]. From a quantitative perspective, financial models based on net present value (NPV) [78,79], and Real Options Theory [80,81,82] 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 sometimes been used instead [83].

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) [84,85] or the 2D bubble diagrams [66] 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 [86]. 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 [87].

It is important to note that "the combination of individually good projects [does not] necessarily constitute the optimal portfolio" [74], 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.

3.3 Spacecraft as a technology portfolio

This chapter proposes the idea that system design is, in several ways, a process similar to the constitution of an R&D portfolio. A spacecraft is here conceived of as a "technology portfolio" or a portfolio of technologies. By focusing 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, this chapter investigates 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 [88], a fundamental systems engineering and design principle similar to the one in portfolio selection is encountered: "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), special emphasis is put in this chapter 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". The definition of "instrument" as a value-delivering part of a spacecraft proposed herein 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. Figure 13 shows a typical "funnel representation" of portfolio selection to illustrate this design process.

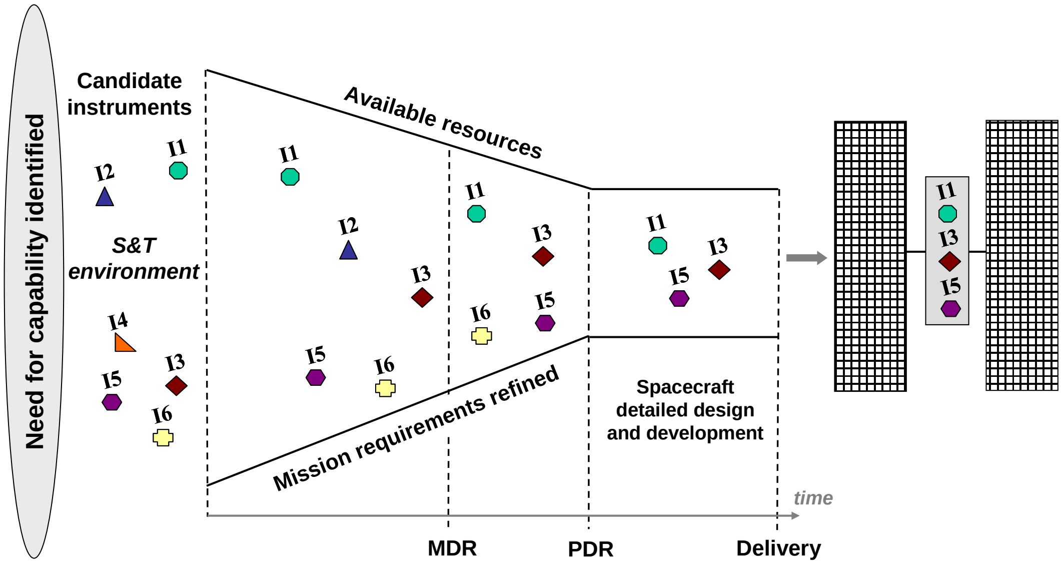

Figure 13. Funnel representation of the design and development of a spacecraft conceived of as a "portfolio of instruments". (Adapted from GAO [70])

Figure 13 is a diagram 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 entrance 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 [25]. 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 Figure 13). As the mission requirements and constraints are refined (moving to the right in Figure 13), 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 [89]. 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).

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. This chapter considers a spacecraft as a portfolio of technologies with a similar mindset and a 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. The impact of these portfolio characteristics on the schedule delivery of the spacecraft and its schedule risk are then analyzed. Finally, this chapter investigates the utility implications of varying the portfolio characteristics and time-horizons, and provides “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 it is argued in section 3.6.2).

3.4 Probabilistic Model of Spacecraft Time-to-Delivery

This section formulates a probabilistic model of the Time-to-Delivery of a spacecraft, $TD_{\mathrm{s/c}}$, based on the idea of technology portfolio. The novel random variable here introduced, $TD_{\mathrm{s/c}}$, which in the 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. $TD_{\mathrm{s/c}}$ is one contribution in this direction.

3.4.1 Model of Instruments Delivery Schedule

The first component of $TD_{\mathrm{s/c}}$ 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 Instruments 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.

3.4.1.1 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. The rest of this chapter uses 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. (3.1):

$$\begin{cases} \mu = \ln\left(\dfrac{m^2}{\sqrt{v+m^2}}\right) \\ \sigma = \sqrt{\ln\left(\dfrac{v}{m^2}+1\right)} \end{cases} \tag{3.1}$$

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. (3.2):

$$f(TD_i, m_i, v_i) = \frac{1}{TD_i \sigma_i \sqrt{2\pi}} e^{-\frac{(\ln(TD_i)-\mu_i)^2}{2\sigma_i^2}} \tag{3.2}$$

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 14.

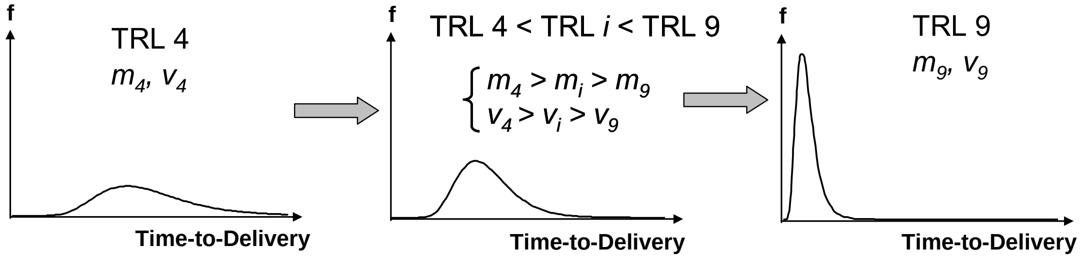

Figure 14. Distributions of Instrument Time-to-Delivery for various values of the initial TRL of the instrument (notional)

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. The complete TRL scale was presented in Table 1.

3.4.1.2 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.

$$\boldsymbol{Pf} = \left[TRL_1 \quad TRL_2 \quad \ldots \quad TRL_n\right] \tag{3.3}$$

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.

3.4.1.3 Instruments Delivery Schedule

The development of the instruments is illustrated in Figure 15, and is carried out in a non-sequential manner, either concurrently or with varying time overlap.

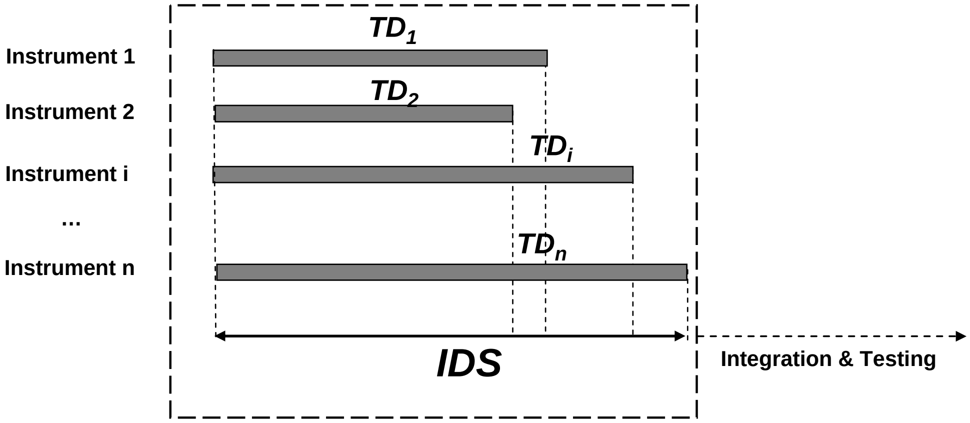

Figure 15. Instruments Delivery Schedule of a spacecraft (notional)

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 Instruments Delivery Schedule). Assuming that the development of all the spacecraft instruments is triggered around the same time (given that the call for and the contracts of all the instruments are usually issued around the same time), the Instruments Delivery Schedule (*IDS*) is defined as the maximum Time-to-Delivery (TD_i) of all the instruments in the spacecraft's portfolio vector[‡‡]. The expression of IDS is shown in Eq. 3.4:

$$IDS = \max_{i \in Pf}\left(TD_i\right) \tag{3.4}$$

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).

3.4.2 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*, the 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, the duration of spacecraft Integration & Testing is referred to as T_{int}. To analyze the impact of the portfolio size on T_{int}, schedule data from 21 NASA spacecraft

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[‡‡] The work presented in this chapter focuses on the modeling of the impact of varying portfolio characteristics on spacecraft delivery schedule (based on a determined number of instruments, and well-defined instruments TRLs). However, for completeness purposes, the model could easily incorporate the bus completion time by using max(TD_i, T_{bus}) instead of Eq. 3.4. This would not affect the design space exploration presented in this chapter.

for which the duration of the I&T phase as well as the number of instruments were available is considered. In this sample, the number of instruments per spacecraft ranged from one to six. Within each of these six categories, the average duration of Integration & Testing was computed, as shown on Figure 16 as a function of the number of instruments.

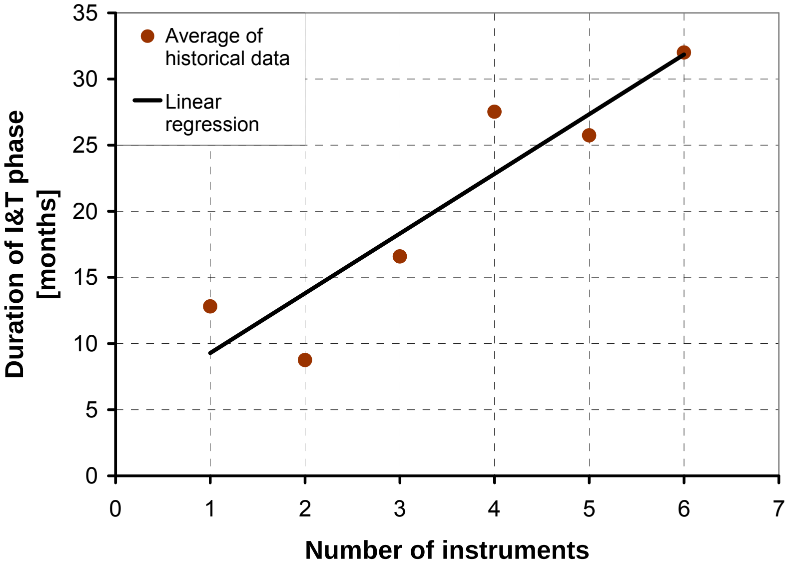

Figure 16. Model of average duration of Integration & Testing as a function of the number of instruments

The visible trend in Figure 16 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. (3.5):

$$\langle T_{int} \rangle = a \cdot n + b \tag{3.5}$$

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 16 indicates 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. (3.5)] are provided in Table 6.

Table 6. Model parameters for the average T_{int} (a,b) and the variance of T_{int} (c) in the data set

Model Parameter	Value
a	4.5
b (month)	4.8
c	74.0

This model however does not capture variability or schedule uncertainty in the I&T phase. To do so, T_{int} is considered as a random variable instead of the single average value provided by Eq. (3.5), and lognormal probability distribution functions are used 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. (3.5), 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 (3.6) and (3.7):

For a given portfolio size *n,*

$$f(T_{int}, m_n, v) = \frac{1}{T_{int}\sigma_n\sqrt{2\pi}} e^{-\frac{(\ln(T_{int})-\mu_n)^2}{2\sigma_n^2}} \tag{3.6}$$

$$\text{with} \quad \begin{cases} \mu_n = \ln\left(\dfrac{m_n^2}{\sqrt{v+m_n^2}}\right) \\ \sigma_n = \sqrt{\ln\left(\dfrac{v}{m_n^2}+1\right)} \end{cases} \qquad \text{and} \quad \begin{cases} m_n = a \cdot n + b \\ v = c \end{cases} \tag{3.7}$$

3.4.3 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 this work, a probabilistic model of the duration of this phase (that is referred to as "Shipping time" in a broad sense) was derived based on data from the 21 NASA spacecraft. Figure 17 shows the distribution of spacecraft shipping time in the sample, along with a lognormal fit of the data.

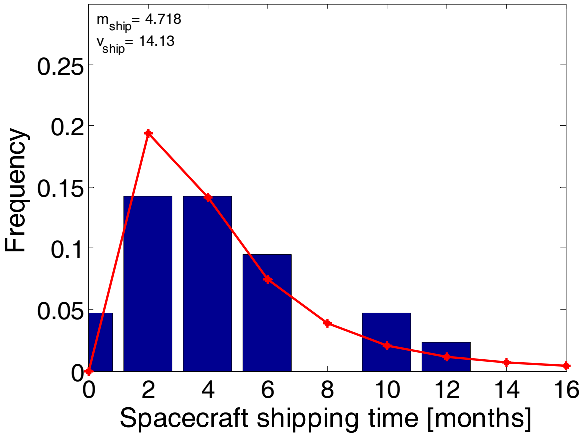

Figure 17. Distribution of the spacecraft shipping time in the data sample and associated lognormal fit

The probability distribution function of the spacecraft shipping time T_{ship} is given in Eq. (3.8):

$$f(T_{ship}, m_{ship}, v_{ship}) = \frac{1}{T_{ship}\sigma_{ship}^2\sqrt{2\pi}} e^{-\frac{(\ln(T_{ship})-\mu_{ship})^2}{2\sigma_{ship}^2}} \tag{3.8}$$

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

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 7.

Table 7. Parameters of the lognormal model for the spacecraft shipping time T_{ship}

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

3.4.4 Monte-Carlo simulations

There are now 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. (3.4)] 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. (3.9)], a numerical simulation method that can reproduce the random nature of the inputs is needed. 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 [90].

The probability density functions of the three input random variables (TD_i, T_{int}, T_{ship}) are given in Eqs (3.1), (3.6), and (3.8). As an illustration of Monte-Carlo simulations, these equations were used to randomly generate 50,000 values for each of these random variables. The intermediate results are shown in Figure 18, Figure 19 and Figure 20. In the subsection 3.4.5, Monte-Carlo simulations are used to derive the end result of interest in this chapter, namely the spacecraft Time-to-Delivery $\mathrm{TD}_{\mathrm{s/c}}$ for varying portfolio vectors, that is for different payload sizes, and different TRL's of its constitutive instruments.

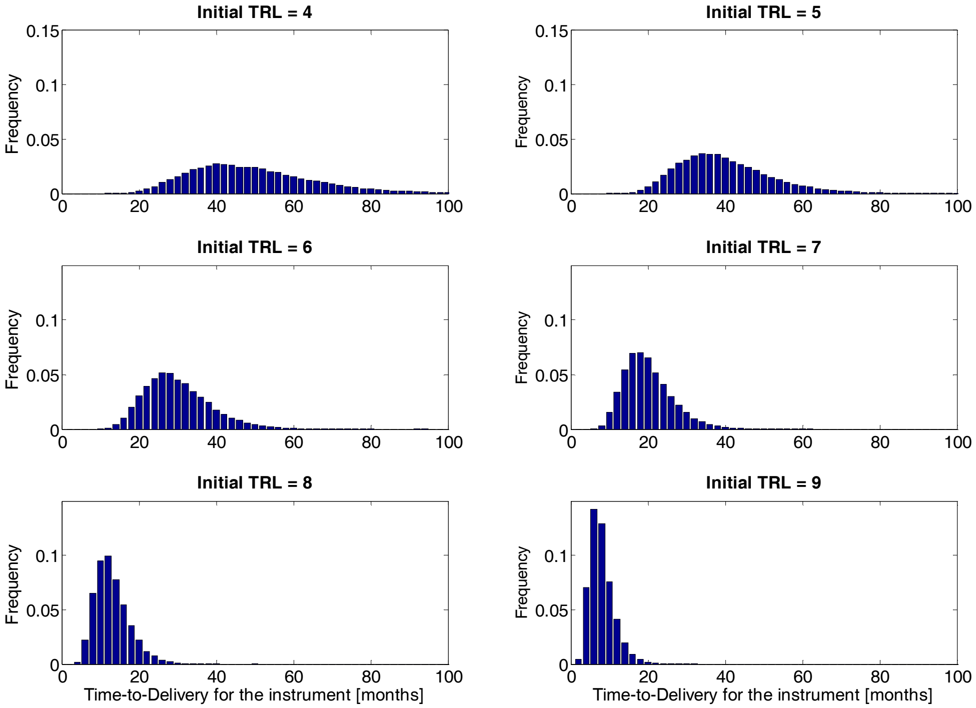

Figure 18. Lognormal distributions of the Time-to-Delivery for the instruments, for each value of the initial TRL

Based on the functional form of Eq. (3.2), Figure 18 represents the six lognormal distributions obtained after generating random values for the Time-to-Delivery of the instruments (first step of the model of Instruments Delivery Schedule), given their initial TRL (from TRL_{ini} = 4 to TRL_{ini} = 9). Note that their form corresponds to the trends presented on Figure 14.

Similarly, Figure 19 represents the six lognormal distributions of Eq. (3.6) 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. (3.7).

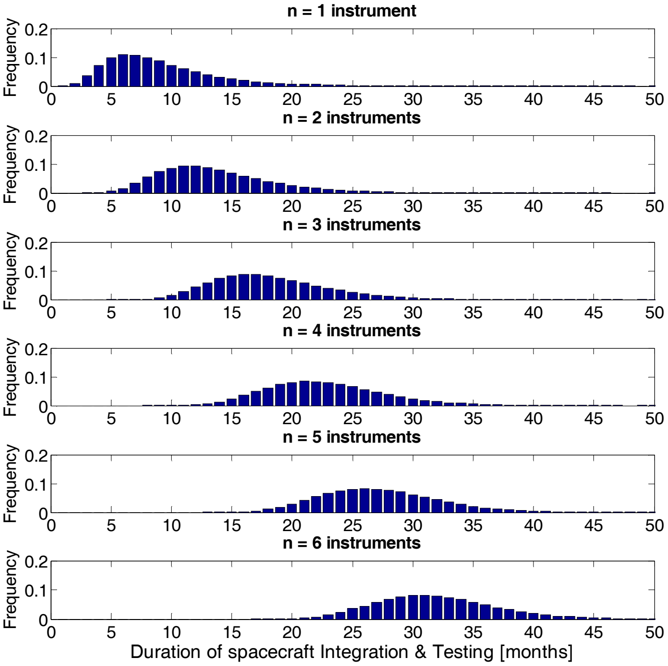

Figure 19. Lognormal distributions of the spacecraft Integration & Testing Time for each value of the portfolio size *n*

Finally, the random data generated for the duration of spacecraft shipping following the model of Eq. (3.8) is shown in Figure 20.

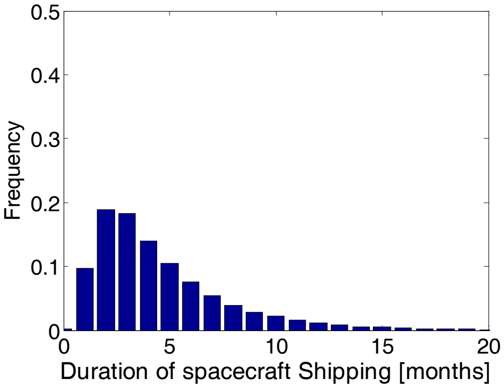

Figure 20. Lognormal distribution of the spacecraft Shipping Time

3.4.5 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. (3.9)]:

$$TD_{s/c} = IDS + T_{int} + T_{ship} \tag{3.9}$$

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 21.

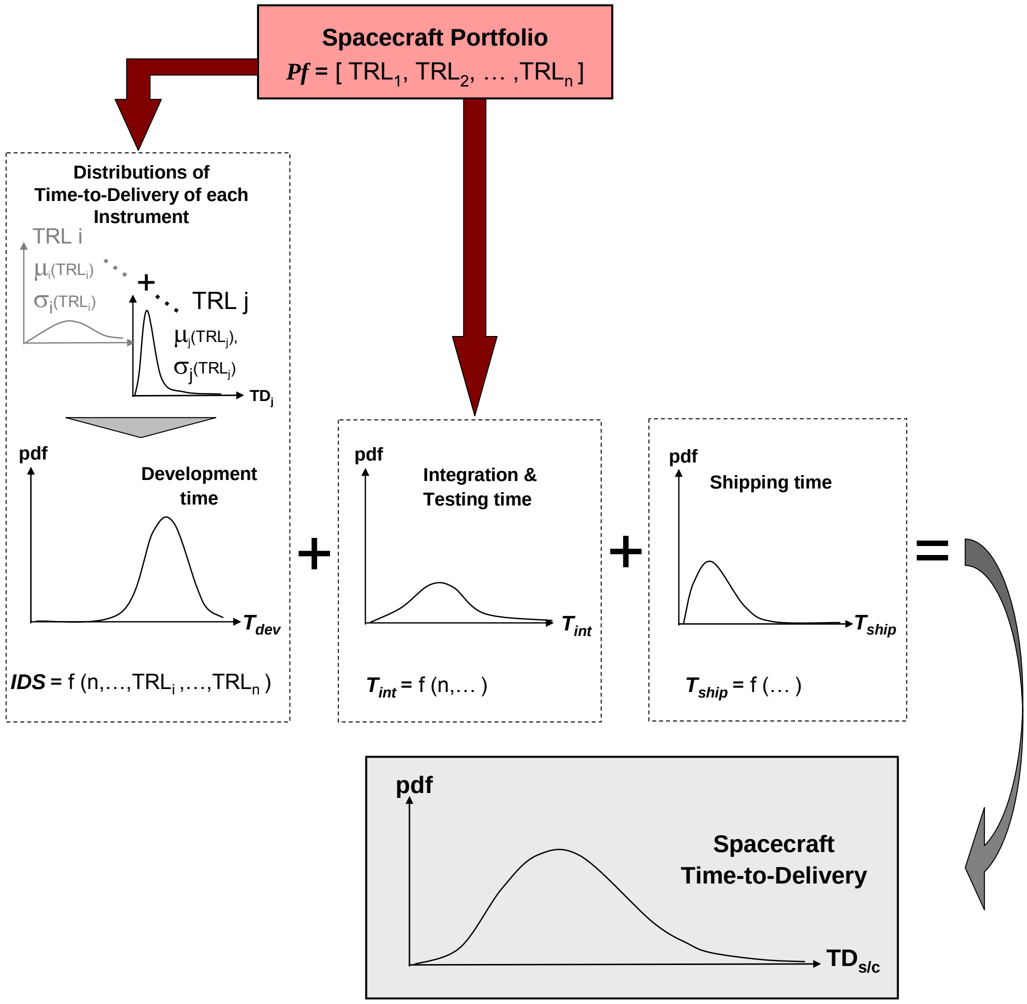

Figure 21. Summary of the model of spacecraft Time-to-Delivery (notional)

3.4.6 Domain of applicability and limitations of the model of time-to-delivery

It is now important to emphasize the distinction between the structure of the model and the data discussed previously that was used to calibrate the model. Figure 21 showed a representation of the structure of the model of spacecraft time-to-delivery articulated around the concept of spacecraft portfolio. The conceptual foundations of this model make it relevant for a variety of applications and analyses whose validity is mainly limited by the availability and nature of the data used to calibrate the model. The only current structural limitation pertains to the assumption that the development schedule of a spacecraft is organized around three main phases that are conducted sequentially. While this may be a reasonable approximation for many common spacecraft, in the case of large and very complex missions such as NASA's Cassini spacecraft, the integration and testing of some subsystems may follow parallel paths while other technologies/subsystems are still maturing and at a relatively low TRL.

In addition to the proposed structure of the model of spacecraft time-to-delivery, which is a main conceptual contribution of this thesis, a quantitative application of this model is presented by using historical data. As discussed in sections 3.4.2 and 3.4.3, the data used to calibrate the characteristic parameters of the distributions of the models of integration & testing time and shipping time included 21 NASA spacecraft for which the duration of the corresponding phases and the number of instruments was known. This dataset contained spacecraft with up to six payload instruments. In this thesis, a portfolio instrument was defined as "an independent value-delivering subsystem of a spacecraft" (as presented in Section 3.3), in a manner that is consistent with the traditional definition of payload instrument used by NASA. As a result, the quantitative results of the analyses of spacecraft time-to-delivery conducted for this thesis are valid for a portfolio size n_{inst} less or equal than six. Several extensions are however possible:

- Should data including larger spacecraft (i.e., with more instruments) be available in the future, valid quantitative results could be derived for values of the portfolio size larger than six.

- Should a different definition of portfolio instrument be adopted (e.g., that extends to other spacecraft subsystems, as discussed in section 3.3), the structure and theoretical underpinnings of the model of spacecraft time-to-delivery remain relevant, and additional data will be required to calibrate each phase duration and to perform the corresponding quantitative analyses.

3.4.7 Metrics of interest

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

1. The first measure is the mean of this output random variable $TD_{s/c}$, which is referred 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, and can be thought of as a proxy for the time constant τ_0, indicator of responsiveness as discussed in Chapter 2.
2. Furthermore, a measure of variability of the spacecraft Time-to-Delivery is considered. Instead of using the standard deviation of the spacecraft Time-to-Delivery, another measure that should prove more useful to system engineers and program managers is introduced, namely the likelihood of overshooting a given schedule estimate, which represents a form of **schedule risk**. More specifically, **a family of schedule risks SR_{mr}** is defined, for various values 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, the Schedule Risk

SR_0 is defined as the probability that the spacecraft Time-to-Delivery exceeds the $MTTD$:

$$SR_0 = P\{TD_{s/c} > MTTD\} = \int_{MTTD}^{\infty} f(t)dt \tag{3.10}$$

f is the probability density function of $TD_{s/c}$ as represented on Figure 21. 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 (here, 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 [91]. 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. (3.11) 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:

$$SR_{mr} = P\{TD_{s/c} > MTTD + mr\} = \int_{MTTD+mr}^{\infty} f(t)dt \tag{3.11}$$

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, in the rest of this chapter the probability of overshooting the *MTTD* by 6 months $SR_{0.5}$ is considered, as well as the probability of overshooting the *MTTD* by one year SR_1, etc.

Figure 22 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, $TD_{s/c}$.

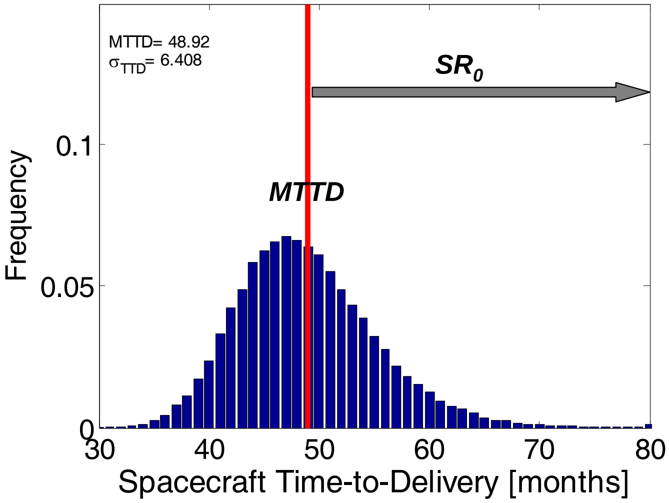

Figure 22. Final distribution of spacecraft Time-to-Delivery $TD_{s/c}$ with *MTTD* and SR_0 (illustrative).

The following section now analyzes the influence of the spacecraft portfolio choice on the *MTTD* and various Schedule Risks.

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

Farquhar and Rao [92] 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, a similar classification is adopted by defining the balance of a spacecraft technology portfolio with respect to the individual TRL of all its instruments. The impact of portfolio choice on *MTTD* and Schedule Risk is investigated, by distinguishing two types of "balance" of spacecraft portfolio: homogeneous TRL cases, and heterogeneous TRL cases.

3.5.1 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.

3.5.1.1 Analysis of Mean-Time-To-Delivery

Figure 23 (left) 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 Figure 23 (left):

1. The *MTTD* of the spacecraft 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 instruments, 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. (3.4)] and Integration & Testing [Eq. (3.5–3.7)] phases, as reflected by Eq. (3.9) and summarized in Figure 21.

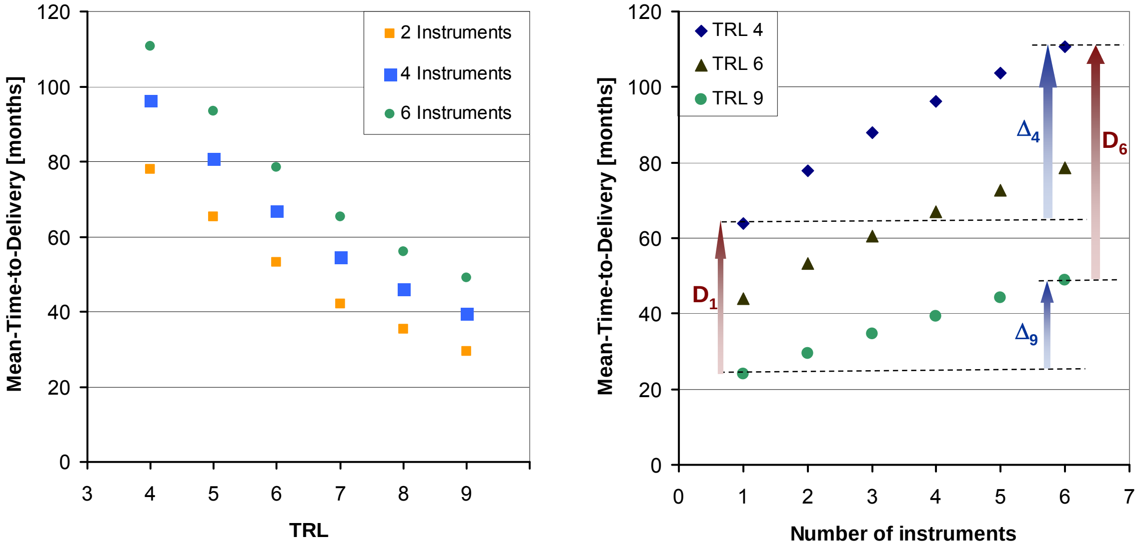

Figure 23. MTTD as a function of the initial TRL of the instruments (left) and as a function of the portfolio size (right)

The two previous results confirm intuition: longer schedules are associated with the use of lower technology maturity, as well as the inclusion of more instruments in a spacecraft.

The right plot of Figure 23 represents the same outputs of the model as those shown in the left plot but from a different perspective that highlights the combined effect of portfolio size and technology maturity. More specifically, it can be seen on the right plot of Figure 23 that:

1. The sensitivity of the *MTTD* to TRL increases when the number of instruments increases. For example, when the spacecraft contains one instrument, the MTTD jumps from 24 to 64 months when the instruments TRL drops from 9 to 4, i.e. a difference of D_1=40 months. However, when the spacecraft contains 6 instruments, the *MTTD* jumps from 49 months to 111 months when the instruments TRL drops from 9 to 4, i.e. a difference of D_6= 62 months. The fact that $D_6 > D_1$ reflects the more significant impact of the instruments TRL for larger portfolios.

2. The impact of an increase in the number of instruments on the *MTTD* is more significant at low TRL. For example, at TRL = 9, the spacecraft's *MTTD* is 24 months with one instrument and it increases to 49 months when the spacecraft contains 6 instruments, i.e. an increase of $\Delta_9 = 25$ months. However, at TRL 4, when the spacecraft development starts with a single instrument, its *MTTD* is 64 months and it increases to 111 months when the spacecraft contains 6 instruments, i.e. an increase of $\Delta_4 = 47$ months. The fact that $\Delta_4 > \Delta_9$ reflects the more significant impact of a portfolio size increase for lower TRLs.

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 section 2.6.2.2.

3.5.1.2 Analysis of Schedule Risk

In addition to the *MTTD* results discussed previously, Figure 24 provides 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 24 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 17% if the instruments' initial TRL is 6 (middle curve in Figure 24).

Furthermore, a vertical cut across Figure 24 reads as follows. For instruments with TRL = 6, there is a 4% 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.

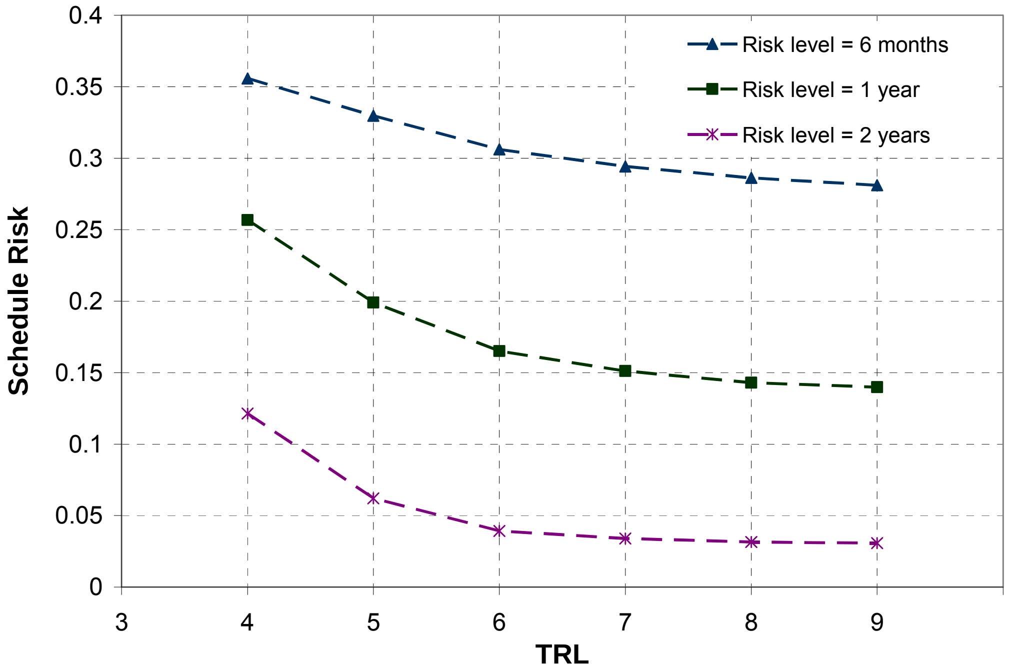

Figure 24. Schedule Risk curves as a function of the TRL of the instruments (*n* = 3), for various risk levels.

The concept of schedule risk curves is particularly important in the design and acquisition of space systems. This chapter's recommendations are 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.

3.5.2 Heterogeneous TRL case

The analysis conducted in the previous subsection was confined to instruments of identical technology maturity at the start of the spacecraft development. This situation was referred to as the "homogeneous TRL case." In this subsection, this constraint is relaxed and spacecraft portfolios with heterogeneous instrument TRLs at the start of the spacecraft development are investigated.

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. Cases of spacecraft portfolios with instruments that have different initial TRLs are now considered, and the impact of this heterogeneity of the technology maturity on the spacecraft mean time to delivery (*MTTD*) and its schedule risk is investigated.

3.5.2.1 Spacecraft portfolios with two instruments

To get a preliminary idea of technology maturity heterogeneity, first consider examples of spacecraft with only two instruments (i.e., the portfolio size is $n = 2$), for which the initial TRL of both instruments at the start of the spacecraft development is varied. Figure 25 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.).

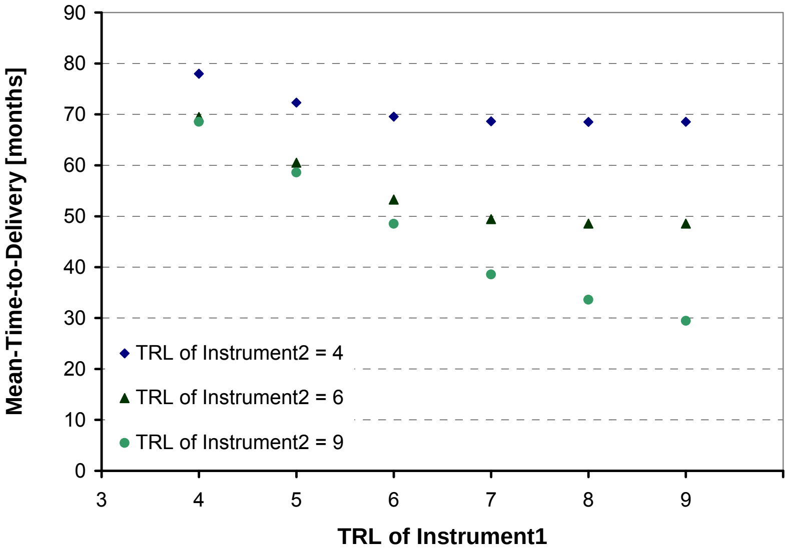

Figure 25. Mean-Time-To-Delivery for heterogeneous TRL cases with 2 Instruments

Note on Figure 25 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. (3.4).

3.5.2.2 Degree of TRL-heterogeneity

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

$$\delta = \sqrt{\frac{1}{n}\sum_i (TRL_i - \mu_{TRL})^2} \qquad (3.12)$$

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 note that 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 3.5.1. 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. (3.12) 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. Both measures however appear equally valid.

As an application of Eq. (3.12), 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 26. 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). For example, the spacecraft with the most heterogeneous portfolio in Figure 26 (***Pf*$_3$** = [4 4 4 6 9 9] with δ_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 ***Pf*$_1$** = [6 6 6 6 6 6] and δ_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.

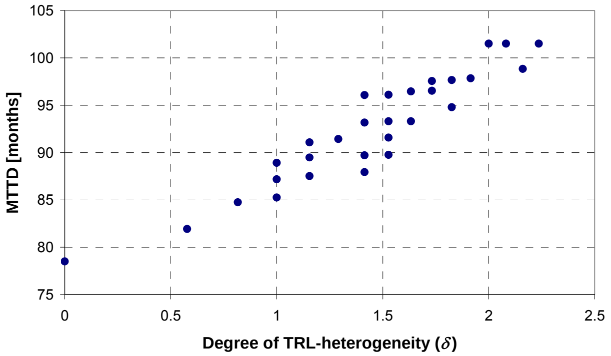

Figure 26. Mean-Time-To-Delivery as a function of the degree of TRL-heterogeneity (δ)

(n_{inst} = 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 ($\delta = 0$) or roughly similar initial technology maturities ($\delta < 1$), rather than TRL-heterogeneous portfolios with both high and low maturity instruments.

3.6 Utility Implications of Spacecraft Time-to-Delivery and Portfolio Selection

3.6.1 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. This section proposes to analyze the cumulative utility provided by the spacecraft (through its instruments) and to identify the portfolio for which, given a time-horizon τ_{ops}, this spacecraft utility is maximized. This analysis 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) [93,94]. 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 the utility analysis, the time needed to perform on-orbit check-ups before the spacecraft is delivered to the customer and starts providing service is neglected). As a result, the model of spacecraft Time-to-Delivery presented in section 3.4 can be used, that is, $TD_{s/c}$ months after the start of the development for the spacecraft to begin delivering services. In the following, the calculation of the cumulative utility is performed starting from $TD_{s/c}$, until the time-horizon τ_{ops} of interest is reached, as shown in Figure 27.

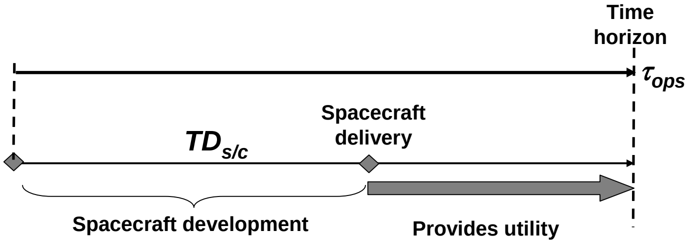

Figure 27. Utility provided by the spacecraft until the time-horizon is reached (notional)

By analogy with the definition of the spacecraft as a Technology Portfolio in Eq. (3.3), the instantaneous utility of the spacecraft is defined as the vector composed of the utility per unit time provided by each instrument:

$$\hat{\mathbf{u}}_{s/c} = \begin{bmatrix} \hat{u}_1 & \hat{u}_2 & \dots & \hat{u}_n \end{bmatrix} \tag{3.13}$$

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:

$$\hat{u}_{tot} = \sum_i \hat{u}_i \tag{3.14}$$

As illustrated in Figure 27, 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:

$$u = \hat{u}_{tot} \cdot (\tau_{ops} - TD_{s/c}) \cdot H(\tau_{ops} - TD_{s/c}) \tag{3.15}$$

$H(\tau_{ops}-TD_{s/c})$ 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 3.5.1. Figure 28 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 28 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 spacecraft delivers utility for a longer time period.

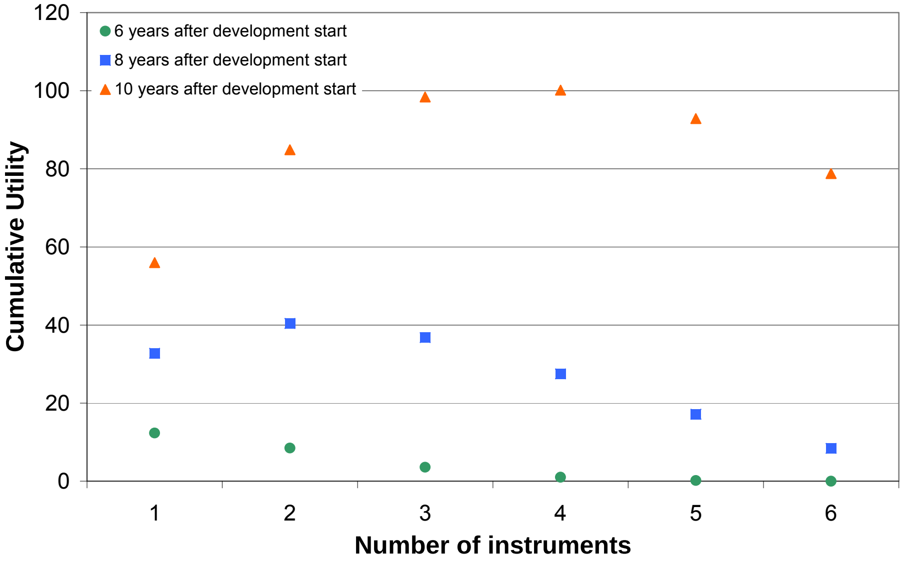

Figure 28. Cumulative utility as a function of portfolio size for different time-horizons ($TRL_{ini} = 4$)

More importantly, the significant result in Figure 28 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, it can be seen on Figure 28 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 27 for clarifications), and, while their utility per unit time will be larger than the single-instrument spacecraft [Eqs. (3.13-3.14)], 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, Figure 28 shows 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.

3.6.2 The paradigm shift needed to design for space responsiveness

Figure 28 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. In this thesis, it is referred to as calendar-based optimization, and is opposed to the traditional clock-based (after launch) spacecraft design and optimization. In the latter, one cares 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 possible 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 29 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.

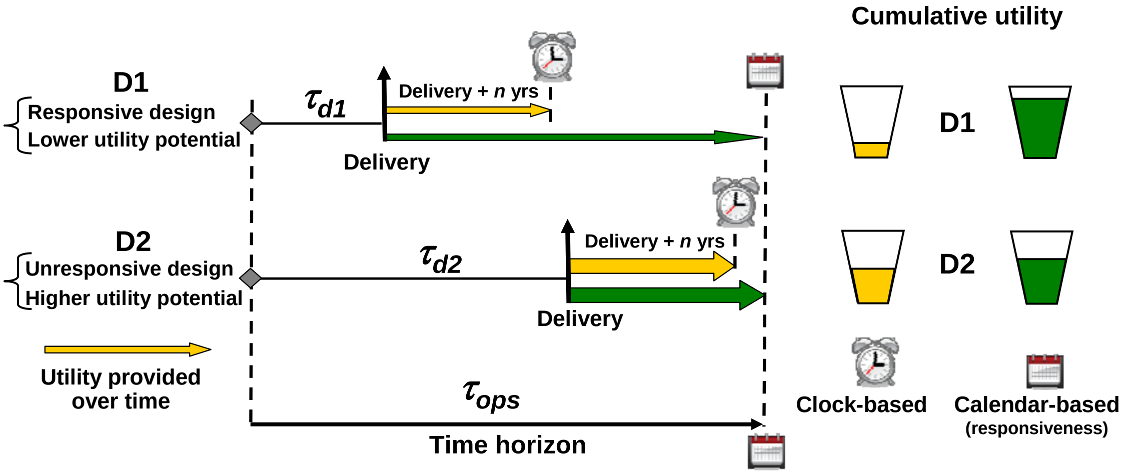

Figure 29. The paradigm shift needed to design for Responsive Space (notional)

In other words, in the calendar-based design approach, the actual timeline of the existence of a need (emergence, evolution and possible disappearance) defines the time-window or time-horizon during which the utility delivered has to be maximized[§§]. In such a mindset, design decisions are thus directly influenced by this timeline.

[§§] Note that the end of the time window does not necessarily imply any discontinuation of the spacecraft. It rather corresponds to the instant at which the cumulative utility delivered by a spacecraft needs to be assessed. (This therefore

Various situations in which space responsiveness is needed can benefit from the application of a calendar-based optimization mindset. For example:

- A calendar-based design mindset can be critical, as noted earlier, in a defense context, where space capabilities may be developed to support a war effort with an initially planned duration. For example, Doggrell reports that "when it became obvious in September 1990, during the planning for Desert Storm, that existing satellite-communications capacity would not support the war effort, we made an urgent attempt to launch an additional Defense Satellite Communications System III spacecraft. That mission finally launched on 11 February 1992, missing the war by over a year!" [95]. This example illustrates that a calendar-based approach that properly reflects the time-horizon of such military operations (1.5-2 years in this example) should help guide design choice to maximize the cumulative utility delivered by the spacecraft.

- The notion of time-horizon may also be relevant for scientific missions, for which science can only be collected during a finite period of time. Specific orbital alignments and design constraints (e.g., amount of available ΔV) only allow the study of certain bodies for a finite period of time, imposing *de facto* a time window during which science can be collected (or utility delivered). For celestial bodies with a large orbital period (e.g., comets on highly elliptical orbits, such as

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may correspond to other events related to that assessment, such as a vote to decide on the budget allocated to a program, or a decision to extend a mission, etc.)

Halley's comet visited by the ICE and Giotto spacecraft), such opportunities do not reoccur frequently, thus precluding the possibility of postponing the launch. With such calendar requirements, a calendar-based approach could prove useful to make the appropriate design decisions to maximize the science return obtained by a spacecraft.

3.6.3 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 30.

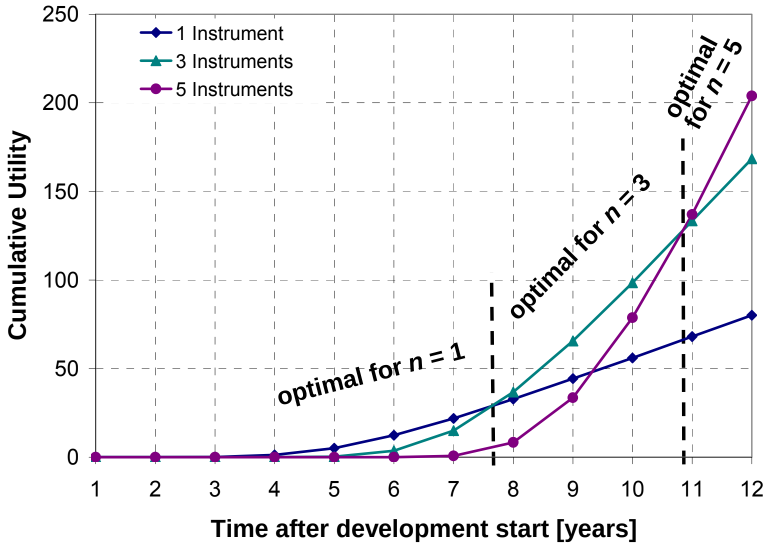

Figure 30. Cumulative utility over time after development starts, for various portfolio sizes (TRL_{ini} = 4)

Using the utility results of Figure 28, "optimal" portfolio sizes that provide the highest utility based on the time-horizon considered can be identified. The results are shown in

Figure 30, 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 30). 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 30).

Next, the TRL dimension is considered, in addition to the time-horizon τ_{ops} to the search of the utility-optimal portfolio size. Recall that the curves in Figure 28 and Figure 30 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 23a), which in turn affects the cumulative utility provided after a given period. The location of the intersection points of Figure 30 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 presented in Figure 31. Figure 31 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 31. 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 31 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).

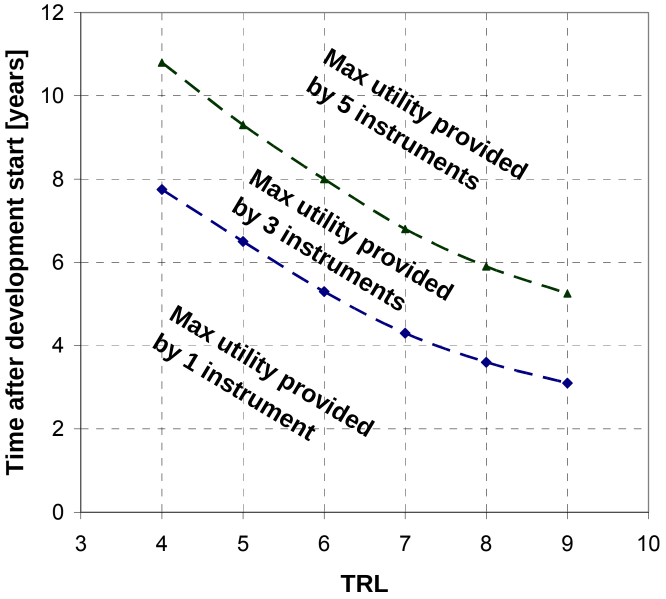

Figure 31. Map of optimal portfolio sizes yielding the maximum cumulative utility

Next, the degree of TRL-heterogeneity is considered and all possible portfolio combinations are evaluated (by varying both n and δ). The results for $\tau_{ops} = 12$ years are shown in Figure 32 in the cumulative utility versus $MTTD$ space.

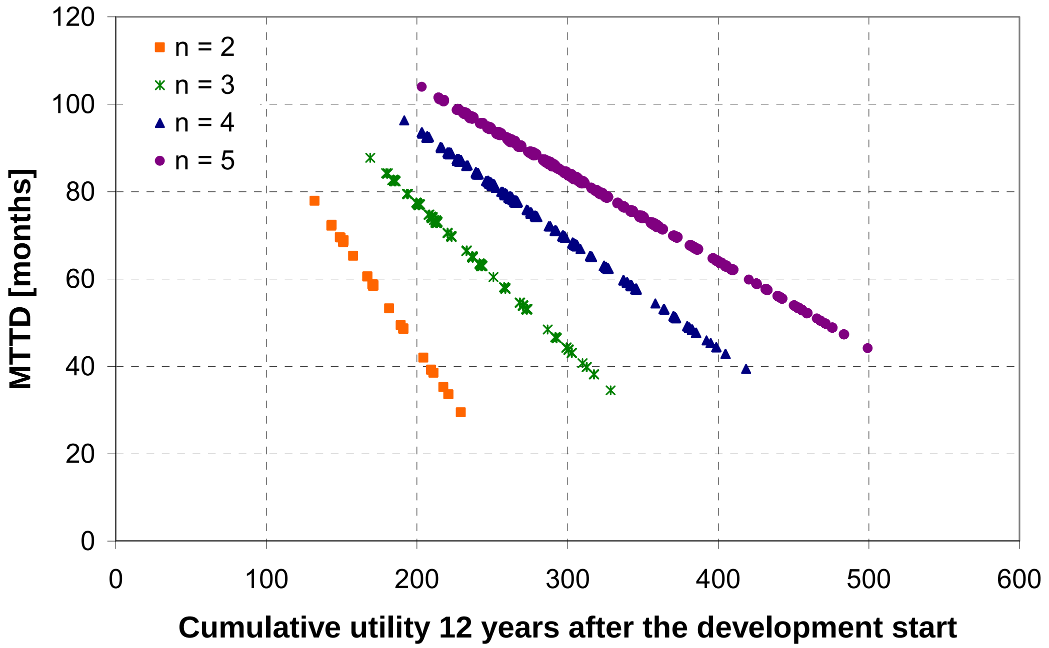

Figure 32. Cumulative utility versus MTTD for all portfolio combinations (for $\tau_{ops} = 12$; shown on the figure are portfolio sizes $2 \leq n \leq 5$)

Two important observations are highlighted based on Figure 32:

- 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 32, 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 32 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. (3.13) and (3.14)). 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. (This assumption of homogeneous utility will be lifted in Chapter 6). Such adjustments would modify the shape of the set of points presented in Figure 32, but would not alter its use and interpretation.

3.7 Summary

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 that end, the notion of portfolio developed by the R&D community was adapted to the micro-level of a single complex engineering system by conceiving of a *spacecraft itself* as a technology portfolio. This chapter 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, a probabilistic model of the Time-to-Delivery of a spacecraft, which includes the development, Integration and Testing, and Shipping phases, was formulated. The resulting random variable Time-to-Delivery (along with its mean and dispersion) is one important characterization of space responsiveness and schedule risk.

Through the variation of the portfolio characteristics, this chapter 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 developed in this chapter 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. Finally, the utility implications of varying the portfolio characteristics and time-horizons were explored, and "portfolio maps" were provided 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.

Note that, in this chapter, the utility delivered by each spacecraft instrument was assumed to be constant over the time horizon of interest. This assumption does not capture an important phenomenon that can result in a loss of value (or appeal) of a spacecraft over time, namely the obsolescence of some (or all) of its components. Located at the other end of the spectrum of technological innovation, obsolescence occurs when new and outperforming technology competes with a current design, or when changes in customer needs or regulations make the services currently delivered by the spacecraft less appealing. When designing to optimize the utility delivered by a spacecraft throughout its lifetime, it appears important to account for the effects of obsolescence.

Before being able to model such effects, it is essential to understand more deeply the phenomenon of obsolescence and to unveil its fundamental causes. In the next chapter, a definition of system obsolescence is thus proposed, and the main obsolescence drivers are identified. Furthermore, the various modeling approaches of the phenomenon adopted by different disciplines are reviewed, in order to support the formulation of a stochastic model of obsolescence of space systems that will be the topic of Chapter 5.

CHAPTER 4

ON SYSTEM OBSOLESCENCE: MULTIDISCIPLINARY REVIEW OF CONCEPTS AND MODELING APPROACHES

“Obsolescence never meant the end of anything, it's just the beginning.”

Marshall McLuhan, Canadian philosopher

4.1 Introduction

In modern society, obsolescence has become a familiar phenomenon experienced in many settings. As noted by Naylor [96]: “[i]n American culture and society, to change clothing styles, automobile design, or computer chips each year is a regular part of the culture.” As a sign that this culture of change is now very deeply enrooted in our societies, numerous scholarly publications address the problem of obsolescence across a large diversity of fields. In fact, a Web search can show that more than 8000 publications raise the question of obsolescence directly in their title. Among other things, one can find: “Will mercury manometers soon be obsolete?”, “Is halothane obsolete?”, “Has in-vitro fertilization made salpingostomy obsolete?”, “Has Antitrust Policy in Banking Become Obsolete?”, “Have online international medical journals made local journals obsolete?”, “Are State and Local Tax Systems Becoming Obsolete?”, “Are R&D Organizations Obsolete?”, “Is prison obsolete?”, “Is Progressive Education Obsolete?”, etc.

In the industry, complex systems are threatened by an increasing risk of obsolescence, as they are often characterized by long design lifetimes that do not match the continuously shorter existence of components on the market [97]. Obsolescence then becomes a serious concern as it significantly impacts the value of owned assets and complicates or even prevents the proper operation of a product. Strategies to mitigate or circumvent obsolescence have been explored but are often very expensive. In 2000, the U.S. Government Accountability Office reported that the budget to "resolve obsolescence and diminishing sources issues" of the F-22 fighter aircraft was estimated to be 1.6 billion dollars [98]. However, other opportunities exist to tackle the challenge of obsolescence by improving our understanding of the issue and ultimately developing our ability to model and predict the problem before it occurs.

To this end, this chapter proposes to clarify the concept of obsolescence, unveil the fundamental causes of this phenomenon, and describe various modeling approaches that have been suggested. As illustrated in the previous Web search example, obsolescence is an issue that is pervasive across many disciplines. Although the definitions of obsolescence emanating from various fields do not necessarily agree with each other, each view on obsolescence can offer additional insight and provide directions to model this phenomenon. While obsolescence is sometimes discussed in the context of abstract entities (e.g., disciplines, laws, processes) or even persons (obsolescence of skills), the purpose of this chapter is to improve our understanding of obsolescence when it pertains to material items that are designed and produced. In this case, it will be referred to as product or system obsolescence.

The remainder of this chapter is organized as follows. Section 4.2 presents the key concepts inherent to the issue of obsolescence and provides a synthesized definition of obsolescence. In section 4.3, the root causes of obsolescence are discussed, and four main drivers of obsolescence are identified. Section 4.4 is a multidisciplinary review of obsolescence, as it has been in studied in economics, operations research, bibliometrics and engineering. It focuses on the phenomenology of obsolescence by looking at how obsolescence manifests itself in each discipline, and reviews the different modeling approaches that have been proposed. Finally, the findings of this work are summarized in section 4.5.

4.2 Key concepts

Obsolete derives from the Latin verb "obsolescere" meaning "to fall into disuse". An obsolete product is thus an item that is "no longer in use", "of a kind or style no longer current", or "outmoded in design, style, or construction" [99]. Following those general definitions, there are several aspects of obsolescence that should be noted:

- By essence, obsolescence is a **temporal phenomenon**: occurring more or less gradually, it is often described as "a loss in value" [100] of an item or "a decline of usefulness over time" [101]. The loss of value resulting from obsolescence is singular in the sense that it applies to a given design rather than a specific unit in a set of identical items. For that reason, it should not be confused with physical deterioration or "aging". A product subjected to physical deterioration will lose its appeal, as its performance or reliability may decline over time. An obsolete product however may very well be brand-new (i.e., newly manufactured) and thus perform as intended[***]. In this case, the loss of appeal results from certain attributes, inherent to its design, that are perceived as "outmoded". In short, obsolescence is a design characteristic and not a product characteristic[†††].

- Obsolescence is a **stakeholder-centric concept**: the notions of value and usefulness appearing in the definitions presented at the beginning of this section imply that obsolescence is observed from the point of view of a stakeholder that *experiences the decline in value* of the item. This point of view is typically of either one of the two following forms:

  a. **The supplier's perspective**, from which a sustained drop of market demand for a product results in a loss of value of the supplier's production output, and can thus be one manifestation of product obsolescence.

  b. **The customer's perspective**, from which one practical manifestation of obsolescence is the impossibility to replace or repair a product through the mainstream market, as suppliers of that item may have decided to cease production. Famous examples of such situations include the end of instant film production announced by Polaroid in 2008, or the end of the 3.5-inch floppy disk production by

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[***] Physical degradation or failures is sometimes referred to as "physical obsolescence" or "absolute obsolescence". In this chapter, the distinction between aging and obsolescence is thus made intentionally.

[†††] even if, by extension, a product will be said to be obsolete when its design is obsolete.

Sony in 2010. Fitzhugh [102] thus considers that obsolescence "occurs when the *last* known manufacturer or supplier of an item or raw material gives notice that he intends to cease production". Penalties resulting from obsolescence (such as cost rises, scarcity of expertise, etc.) can even be experienced as soon as the pool of suppliers *starts* being reduced. This is the challenge faced by the U.S Department of Defense with many of its complex systems, and referred to as diminishing manufacturing sources and material shortages (DMSMS): "DMSMS concerns the loss or impending loss of manufacturers or suppliers of critical items and raw material due to discontinuance of production." [103].

- Finally, obsolescence pertains to the **external world**: it is "due to changes in external circumstances over time" [104]; it results not from the "conditions or past operation history [of a product] but [from] a change in the external scenario of technological evolution and marketing" [105,106]. The obsolescence of an item is thus tightly tied to an external environment that provides referents, against which the value of an item is assessed, and constantly updated. The geographical, political, economical and social contexts in which a product (or concept) operates is therefore essential to the definition of its state of obsolescence. Consider the following example: between the 1950's and 1970's, China strictly limited any interaction with the international technology community. Tan [107] explains that "[a]s a result, self-reliance and technology nationalism were achieved for China's R&D system, with the cost of having low-level and obsolete technologies […]. The gap between Chinese technologies and the most advanced Western technologies were often a few decades

> apart." Chinese technologies were clearly obsolete with respect to Western standards, but since China remained isolated from the rest of the world, the economic implications of this obsolescence *within the Chinese* market were not experienced according to Western standards. It is therefore important to acknowledge this subtlety and recall that obsolescence is a spatially relative notion. A product design is never obsolete in itself, but with respect to the expectations of a given community of users or society.

In the light of the characteristics of obsolescence discussed previously, a synthesized definition of product obsolescence is now proposed:

Obsolescence is the decline of value of a product over time, due to a change in the stakeholder's expectations resulting from exogenous events.

Unlike in the case of physical degradation (wear-out), a product that becomes obsolete retains the same design attributes. It is the changes occurring in the external world that result in the inability of the product to meet the stakeholder's expectations. What external changes can result in the obsolescence of a product? This question is addressed in the following section, which identifies and discusses the various drivers of obsolescence.

4.3 The drivers of obsolescence

To fully comprehend what obsolescence is and what its impact may be, it is essential to first understand what processes are at its origins. Much of the existing work on obsolescence has focused on its manifestations (which will be reviewed in section 4.4), sometimes with limited insight on the factors involved in its creation. In this section, the root causes of obsolescence are discussed and four main drivers are identified: technological innovation, network externalities, regulatory changes and need disappearance.

4.3.1 Technological innovation

The most commonly perceived form of obsolescence can be referred as “technological obsolescence”[‡‡‡]: it is the process by which a product becomes obsolete due to the emergence of “challenger units displaying identical functionalities, but with higher performances” [108]. Stated alternatively, “technological obsolescence is caused when the functional qualities of existing products are inferior to newer models” [109].

The history of the lighting industry provides a good example of the technology obsolescence caused by innovation. Oil lamps had been used for thousand years when the Argand lamp, which offered significant improvements in terms of brightness and steadiness of the flame, was introduced in 1780. As a result of the introduction of Argand’s new design, the previous and traditional designs of oil lamps were soon rendered obsolete, and the Argand lamp became the most common lighting device throughout Europe for over 70 years. Later, a new major revolution occurred when Edison combined the invention of the incandescent light bulb with his system for electricity distribution. This rapidly resulted in a wide replacement of the traditional oil and gas illumination in favor of electric lighting starting from the 1880’s [110].

[‡‡‡] Technological obsolescence is preferred over “technical obsolescence”, which often refers to the obsolescence of the technical skills of the workforce.

Obsolescence due to technological innovation has become a much familiar phenomenon with the quasi-omnipresence of electronics in modern society. Another famous example of technological obsolescence concerns audio and data recording. Magnetic tapes, that were widely used throughout the 1980's, were rendered obsolete in the 1990's as they were progressively replaced by Compact Discs which provided a more efficient way of storing information. As buyers became accustomed to the higher capacity, higher sound quality and longer lifetime of the CD technology, their interest towards magnetic tapes declined. Similarly, slide rule calculators had been widely used for decades by engineers and scientists until the 1970's when Hewlett-Packard and Texas Instruments released pocket-sized versions of electronic calculators. These new devices rapidly supplanted slide rules as they allowed much more straight-forward and accurate calculations than their predecessors for an acquisition price that quickly became comparable.

In the previous examples, a new technology fulfilled the same function (e.g, providing lighting, recording data, or performing calculations) than an older concept but with an increased performance, reliability, or efficiency. In this case, the obsolescence of the product directly depends on the improvements offered by the technologies competing in the same environment or market. For a given customer need, Figure 33 illustrates how older designs are progressively "pushed" to the obsolescence zone following the emergence of a more innovative design. The two notional graphs represent two consecutive "snapshots" of the design space (or market), separated by a given time interval Δt. On the left graph, the designs D1 and D3 are leaders on the market, while D3 is becoming outmoded and D2 is already considered obsolete. On the right graph, the emergence of an innovative and competing design D5 that provides better performance raises the users' expectations, which are no longer met by older designs; as a result, D1 and D4 fall into the obsolescence zone.

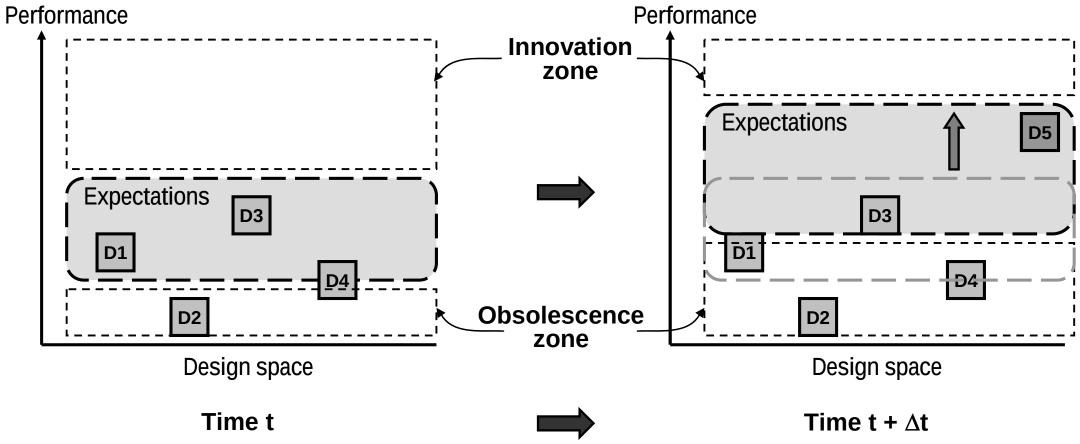


Figure 33: Obsolescence under technological innovation (notional)

On Figure 33, designs are considered obsolete when they become "inferior" to newer competing designs. However, the performance metric used on the y-axis to compare designs and to assess whether some have become obsolete need not be interpreted in a strict sense. Other metrics than quantitative performance may result in the obsolescence of a product due to the emergence of a "better" design. For an equivalent absolute performance output, a product may be rendered obsolete by newer competitors if its reliability is lower, that is, if failures occur more frequently than with newer designs. For example, in defense systems (in particular in avionic computer systems), newer technology is often pursued to increase reliability, "for systems of equivalent performance and cost" [111]. Efficiency improvements and ultimately cost reductions obtained through technological innovation are also reasons for the obsolescence of certain products. For example, in the 1860's, kerosene rapidly superseded whale oil in most oil lamps as its cost was significantly lower than that of whale oil. Similarly, although Edison's first models of incandescent light bulbs provided a similar brightness than that of gas devices (Edison's bulb provided 13 watts against 12 watts for gas jets), the overall system was low in complexity for the user [112] and was initially marketed by Edison himself as a "cheap and practical substitute for illuminating gas" [113]. The relative simplicity and low cost advertised by Edison were key elements that contributed to the wide acceptance of electricity as a replacement for gas lighting.

Note that, in accordance with the definition of obsolescence proposed previously, technology innovation is a driver of obsolescence *when it applies to a given need*, that is, when it pertains to a defined set of users expectations. Technologically superior alternatives do not necessarily drive other designs obsolete if they target a specific group or "niche" of users. For example, due to its uniqueness and the prohibitive cost of its flights, one could hardly consider that the supersonic passenger airliner Concorde did render the existing fleets of subsonic airplanes obsolete. One important factor that decides whether or not a technology has become obsolete is the degree of penetration of competing alternatives, which is intrinsically related to "network externalities" as discussed in the next section.

4.3.2 Network externalities, standardization and compatibility

4.3.2.1 Network externalities

Another driver of obsolescence pertains less to technology innovation strictly speaking and the benefits provided by a new technology than to the penetration and the adoption of a given standard by the community. For similar levels of performances, two or more technologies can compete and very often, only one of them may reach a dominant position. While the other product might fulfill the intended function as well, it can become essential to adopt the dominant model in order to communicate and do business with the rest of the world. Katz and Shapiro [114] define *network externalities* as the force acting when "the utility that a given user derives from the good depends upon the number of other users who are in the same network." Here, obsolescence is thus a decline of value, not triggered by the emergence of an outperforming product, but by another type of external change, the **adoption of a standard as a direct result of network externalities**. Some of the value of many of the systems used today often resides in the number of adopters of the same design. Sometimes this value is simply related to the easier and cheaper usage and maintenance of the dominant design (due to the prevalence of the available parts); sometimes, this value is intrinsically related to the functionality of the product itself, when the product must be used as part of a network, or work in conjunction with other products. This is typically the case for the standards adopted in electronics or information technology. A famous example of this phenomenon can be found in the emergence of Microsoft Windows as the dominant Operating System for Personal Computers since the 1990's. For most computer users, it quickly appeared necessary to adopt this system in order to be able to exchange files with the rest of the world. As a result, rival systems such as IBM OS/2 were much less popular, and became obsolete until they eventually got discontinued.

4.3.2.2 Standardization

Gandal [115] suggests that "expectations of consumers regarding the future size of a network are critical in determining the adoption of network products. Thus consumer expectations that one technology will become a standard may indeed lead to that technology becoming the standard." This principle is consistent with the general definition of obsolescence proposed in section 4.2: in a network, products based on one design retain most of their value as long as the users still expect that said design will become the dominant one. If market dynamics follow a different path by favoring another candidate, users' expectations change and the initial design becomes obsolete, due to network externalities. This was the case during the tough war that opposed JVC/Matsushita's VHS and Sony's Betamax standards for video recording. As VHS showed a consistent technological lead (each subsequent version of VHS allowed longer recording times than the competitor Betamax) [116], it imposed itself as the dominant design. Note however that the obsolescence of Betamax was less driven by the small technological advantage of VHS than by the fact that everyone (i.e., consumers, movie distributors, VCR manufacturers) soon chose to adopt VHS as the standard. The utility derived from the one format was clearly dependant upon the total number of users of that format (and in turn reflected by the number of movies and VCRs sold for that format). Betamax thus became obsolete mainly as a result of the network externalities ruling the videotape industry and the fact that only one standard would survive. Gandal [115] indeed observes that "competition in network markets is likely to lead to standardization on a single technology. In other words the long-term co-existence of competing incompatible standard is unlikely. This is because a small initial advantage will likely influence consumer expectations about the adoption of a particular standard. This in turn will lead to more consumers adopting the standard" [115]. This observation is echoed by Arthur's analysis of "technology lock-in" that considers that "insignificant circumstances become magnified by positive feedbacks to 'tip' the system into the actual outcome selected" [117].

In some cases, the dominant design or standard is even considered *a posteriori* as technically inferior to its competitors, as argued by Liebowitz and Margolis [116]. One famous example of this situation is discussed by David [118] and concerns the keyboard layouts for typewriters and computers. August Dvorak and W.L. Dealey patented in 1932 a keyboard arrangement named Dvorak Simplified Layout (DSK) that aimed at avoiding some of the disadvantages of the QWERTY keyboard. Although DSK resulted in an "increased efficiency" and let "you type 20-40% faster" as advertised by Apple [118], it failed to replace QWERTY as the standard for keyboard. Resistance to adoption was strong due to the network externalities, that is, an important penetration of the QWERTY keyboard at the manufacturer level (machines and processes were designed to produce QWERTY keyboards) and at the user level (typists were trained by default to use QWERTY). As a result, DSK is considered obsolete by many.

This example confirms the idea that obsolescence is not always driven by technological lag (as described in section 4.3.1) but by a process different in nature, namely network externalities.

Figure 34 illustrates how network externalities can result in the obsolescence of a product. In this example, when design D1 is released, the number of its adopters quickly rises, showing the sign of an initial success. Design D2 is released concurrently but proves less successful initially than D1. At this stage of the products' lifecycle, the initial users' expectations in terms of general adoption of a design remain unclear (i.e., low in terms of number of adopters), as users still ignore in what direction the market will evolve. After a certain time, the adoption of D2 takes off while the initial success of D1 proves actually unsustainable and the number of adopters of D1 declines. At this time of the product's lifecycle, the users' expectations are clearer. The design adopted by the majority soon becomes the standard (D2), while competing designs with fewer adopters become obsolete (D1).

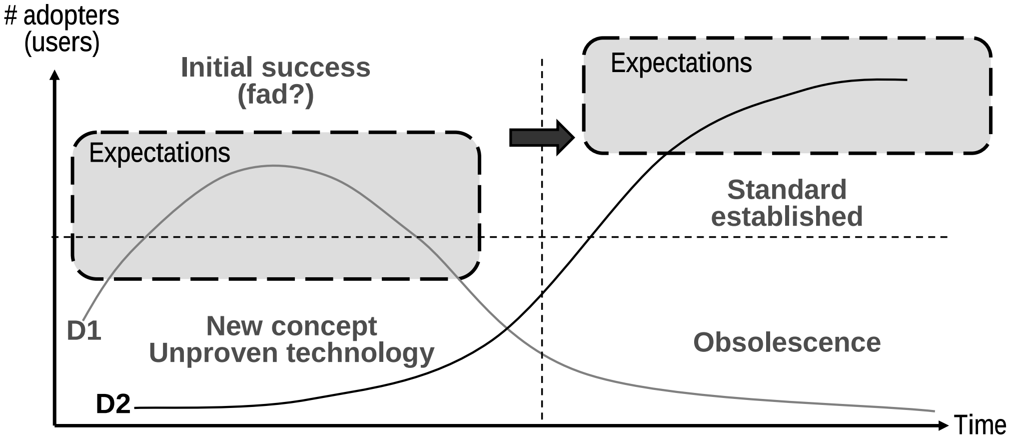


Figure 34. Obsolescence under network externalities (example)

4.3.2.3 Intersystem compatibility and the propagation of obsolescence

After the establishment of a given design as a standard, obsolescence does not only affect the competing designs, but also any product that depends on or interacts with those non-standard designs. In the engineering world, compatibility is the ability "to work with another device or system without modification". With complex systems that are characterized by a high degree of parts coupling and that operate by interacting with other products, obsolescence propagates from subsystem to subsystem due to compatibility requirements. This is typically the case in computer engineering where software and hardware are highly interdependent. Programs designed to run on a given platform are likely to become obsolete if this platform becomes obsolete itself. Sandborn and Myers refer to this interdependence in the commercial-off-the-shelf world as a "symbiotic supply chain relationship where hardware improvements drive software manufactures to obsolete software, which in turn cause older hardware to become obsolete […]." [119].

4.3.2.4 Product obsolescence as the inverse of product diffusion

The two drivers of obsolescence that have just been discussed are inherent to the emergence and the adoption of technologies. Modeling this adoption of innovations is precisely the purpose of the diffusion models that have flourished since the work of Mansfield [120] and Bass [121] (see Mahajan et al. [122] for a review). A few of these models even feature more explicit connections with the problem of obsolescence, addressing the problem of technology substitution by looking at the influence of a second product generation on an earlier one [123,124,125]. Overall, most of these models have in common that they include two effects contributing to the diffusion of a product: innovative adoption and imitative adoption [121,126,125]. Note the similarities with the two drivers of obsolescence discussed previously. Based on those two sole effects (innovation and imitation), a symmetry is apparent between the way to conceive the adoption of a product (diffusion) and the way to conceive the opposite trend, that is, the loss of appeal of a product (obsolescence). However, beyond those conceptual similarities, there exist other phenomena that can specifically drive obsolescence, such as regulatory changes and the disappearance of a need. These two drivers are discussed in the following sections.

4.3.3 Regulatory changes

Section 4.3.1 discussed one form of obsolescence, namely technological obsolescence, through which expectations of individual users are raised with the emergence of innovating designs that offer performance improvements. Similarly, expectations of users can change over time as a communal process, especially when collective attributes, such as safety, order, comfort, etc., of a group are sought to be improved. To do so, organized communities regularly set up rules and standards that reflect the desired improvements and new requirements (which are often hardened). As a result, "design standards and government codes define criteria for obsolescence," as noted by Lemer [127]. Norms are redefined by governments on a regular basis to ensure higher levels of safety, efficiency and comfort. This includes, for example, power limits for wireless transmitters [128], norms for accessible design [129] (to allow infrastructure access by disabled people), building seismic standards, motor vehicle emission standards [130], etc. As these norms are constantly revised, old designs become *de facto* obsolete with respect to society's regulatory needs.

Although somehow related to the two previous drivers discussed previously, there are subtle but important differences that characterize regulatory changes as a driver of obsolescence. First, unlike standards that emerge through network externalities in a non-deterministic fashion (i.e., combination of adopters imitation and random events), new regulatory standards result from conscious decisions and collectively planned events. For example, increased awareness of the health risks posed by asbestos led the European Union to prohibit the use of all asbestos fibers in 2007 [131], rendering it obsolete for building construction purposes. Second, while technological innovation may have initiated the obsolescence process (by making superior alternatives available), it is the new regulations that establish the new designs as the standard, accelerating the obsolescence phenomenon at a full scale. For example, despite the introduction of digital television sets in the early 2000's, analog devices were still prevalent in the U.S. The coup de grâce to traditional analog TV sets was in fact delivered on June 11, 2009, the date chosen by the U.S Federal Communications Commission (FCC) to end all analog TV broadcasts, rendering the old TV sets completely obsolete. In some cases, individual users may not have any incentive in upgrading the technology to meet the new requirements (e.g., a car fulfills the same function for a user whether it pollutes a lot or not), but it is society at large that recognizes that standards should be revised for the common interest.

4.3.4 Disappearance of a need

A last form of obsolescence results from the disappearance of a given need, that is, when the purpose served by a product is no longer relevant. Brown et al. [132] mention that "[o]bsolescence may occur, for a particular item, because the function served by that item is no longer required". While in certain cases technological innovation might initiate a decline in the demand for a product, many other external influences directly determine the need for a given function. These external factors can be sociological, scientific, political, environmental or even media-related. Bradley and Dawson [133] give the example of the disuse of sections of Roman roads: "Whilst roads, in general, are not yet obsolete, some roads will become functionally obsolescent as the destination is no longer in use."

In science, when the progress of knowledge invalidates old theories and/or ancient practices, the associated systems become naturally obsolete. This is for example the case in medicine when archaic bloodletting techniques that were usually more harmful than helpful finally disappeared, resulting in the obsolescence of its associated instruments (e.g., the "scarificator" developed in the 17th century [134]).

Changes in the political environment may also result in obsolescence. For example, as tensions between the United States and the Soviet Union culminated in the early 1960's, the Kennedy administration started to publicly advocate the use of fallout shelters to ensure the protection of the population against a nuclear attack. The U.S Congress "appropriated $207.6 million for Kennedy's shelter program." [135]. On the commercial side, "there were expectations that annual sales could run between $2 billion and $20 billion, and that shelter building would achieve the magnitude of other federally promoted programs such as highway building and urban renewal." [136]. While actual sales never really met these initial expectations, the end of the Cold war definitely put an end to the perception that home protection against a nuclear threat could be needed. Observing "a lack of advertising and consumer demand for home fallout shelters and home radiation monitoring devices", the U.S Federal Trade commission no longer provides guides to regulate them [137], a sign that those devices have indeed become obsolete. Unlike in the case of obsolescence driven by technological innovation as discussed in section 4.3.1, no superior alternative emerged, but the need simply disappeared, making such equipment obsolete.

Finally, some authors sometimes mention a form of "psychological obsolescence", which pertains to the decline in desirability of certain products due to styling reasons, fashion cycles and fads. Discussing this "planned obsolescence of desirability", Packard [138] cites Paul Mazur: "style can destroy completely the value of possessions even while their utility remains impaired". This phenomenon can be considered as the result of the combination of the disappearance of a "need" (i.e., the subjective interest in a given style) fueled by network externalities (the external pressures of society).

In conclusion, it is important to recognize that the drivers of obsolescence as they have been presented are rarely completely uncoupled, and often act as positive feedbacks for each other. Technological innovation can push the adoption of designs in a given direction, reinforced by network externalities, and regulatory changes are also frequently decided in the context of technology advancement and can help precipitate obsolescence. As the challenge of obsolescence affects many areas of modern society, various disciplines have attempted to address this issue in one way or another. The next section now reviews the different modeling approaches that have been proposed in the literature.

4.4 A multidisciplinary review of obsolescence

This section discusses the phenomenology of obsolescence, by presenting the various manifestations of obsolescence across different disciplines, namely in economics, in operations research, in bibliometrics and in engineering. It reviews the modeling approaches that have been proposed in each field and ultimately provides opportunities to learn from each contribution.

4.4.1 Obsolescence in economics

4.4.1.1 Definitions

Obsolescence in Economics has traditionally been discussed in the context of depreciation. Various concepts of depreciation exist within the community of economists, leading to different usages of the term “obsolescence”. This chapter shall principally focus on the common definition of depreciation as the decline of value of an asset over time, or a “rate of decrease of value” [139]. According to Hill [140], depreciation “involves the value of the same asset at two different points in time”, and can be expressed in a simple mathematical form:

$$D = -\frac{dV}{dt} \tag{4.1}$$

where V_t represents the value of the asset at the instant t. For example, the depreciation D over one year can be expressed as $D = V_t - V_{t+1}$. The Bureau of Economic Analysis (BEA) does include obsolescence in its definition of depreciation: “the decline in value due to wear and tear, obsolescence, accidental damage, and aging.” [141]. Building on a discussion reported by Hicks [142], Hill [140] suggests to be more specific by insisting that it is the “foreseen obsolescence” (i.e., related to the expected rate of technological change) that can be treated like wear and tear. Overall, note that this inclusion of obsolescence as a form of depreciation is consistent with the definition of obsolescence of section 4.2 as a “decline in value over time”. The form that this decline is assumed to take over time is discussed next.

4.4.1.2 *Models of depreciation*

Fraumeni [143] describes the different patterns of depreciation proposed by the community of economists. Since the 1950's, the BEA has used straight-line depreciation, which assumes a constant depreciation *D* over the lifetime of an asset:

$$V(t) = V_0 - Dt \tag{4.2}$$

so that the decrease in value between to consecutive years is constant:

$$V_i - V_{i+1} = D \tag{4.3}$$

Figure 35 (left) represents the constant decline of value over time due to straight-line depreciation.

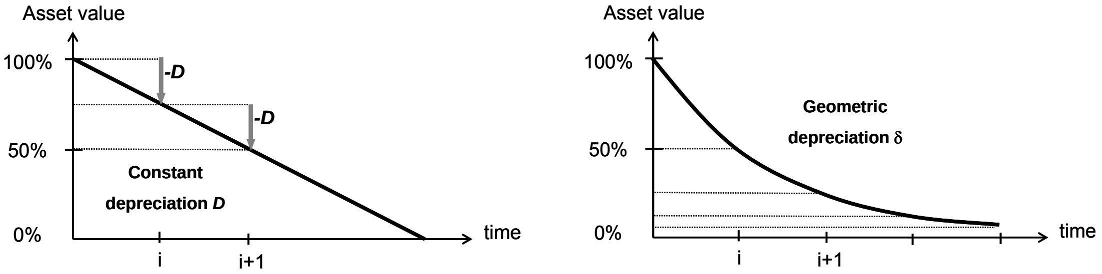


Figure 35: Straight-line depreciation (left) and geometric depreciation (right)

Later work progressively promoted a shift towards accelerated patterns of depreciation, in which depreciation is higher during the first years of the asset lifetime. A geometric law constitutes a simple example of such a pattern, in which the value of the asset at a given year is a constant fraction of the value of the asset the year before, with δ representing the geometric rate of depreciation:

$$V_{i+1} = V_i \delta \tag{4.4}$$

As a result, the value at any year *i* can be related to the initial value of the asset through the relation:

$$V(t=i)=V_0\delta^i \tag{4.5}$$

Figure 35 (right) represents the evolution of the value of an asset over time under a geometric depreciation, which is the model adopted by BEA as the default for "all assets except for computers and computer peripherals, nuclear fuel, autos and missiles" [143]. The corresponding geometric rates of depreciation used by the BEA were derived from the research conducted by Hulten and Wykoff [144] and are organized by categories of assets [145].

4.4.1.3 Obsolescence and aging

However, Hulten and Wykoff [144] and Fraumeni [143] distance themselves from the mainstream conception of depreciation and insist on analyzing the change of value of an asset along two dimensions, by separating the effects of time and the effects of asset age. According to this approach, "economic depreciation is by definition, the decline in price along the age dimension, the partial derivative of price with respect to age" (holding time constant) [144]. "Revaluation" is then the term chosen to describe the decline in price over time (holding age constant), due to inflation or obsolescence.

This chapter shall build on and rise above this semantic argument by simply recognizing that:

- Obsolescence is a temporal phenomenon, that contributes to the decline of value of an asset over time (in agreement with the Hotelling [139] and Hill [140] approaches)

- Obsolescence is distinct from the decline of value due to aging or physical decay (in agreement with the distinction highlighted by Hulten and Wykoff [144] and Fraumeni [143])

Based on those two conclusions, the patterns of “depreciation” presented previously constitute relevant examples that can inspire the modeling of the decline of value due to obsolescence.

4.4.2 Obsolescence in Operational Research

4.4.2.1 The risk of inventory obsolescence

While obsolescence is a concept that is most of the time defined through the relationship between a product and the users of this product (as discussed in section 4.2), it is not exclusively observed at the customer-level. Most studies of obsolescence in Operational Research focus on inventory management, adopting an approach that is therefore supplier-centric. If demand for a product suddenly decreases because of obsolescence, the remaining inventory has little or no salvage value from the point of view of the supplier [146,147]. This effect reflects the obsolescence of the stocks. From an operational research perspective, it is therefore crucial for managers to be able to model the risk of obsolescence of their stocks, since cost penalties are associated with both the production and the storage of items: first, production expenses of the obsolete items represent an investment with no return; second, resources must be spent to store obsolete items before they can be discarded. Managing the inventory efficiently thus requires finding the optimal lot size so as to minimize these costs of obsolescence [148].

4.4.2.2 Models of demand lifetime

The traditional inventory management view on obsolescence is characterized by the "sudden obsolescence" or "sudden death" assumption, under which obsolescence is considered to occur at a single point in time at which the demand suddenly collapses [149,150,132,151,146,148]. As formulated by Brown et al. [132], "[b]efore that date the item is not obsolescent, after that date it is obsolescent, that is, all demand permanently ceases." (This type of behavior is sometimes described by economists with the term "one-hoss shay", a reference to the poem by Oliver Wendell Holmes Sr. "The Deacon's Masterpiece or the Wonderful One-Hoss Shay" presenting a fictional deacon that would last a hundred years until it breaks down all at once; see Saleh, [152]). The corresponding time-to-obsolescence T_{obs} for such an item is illustrated in Figure 36, where the time origin is taken at the instant of initial production.

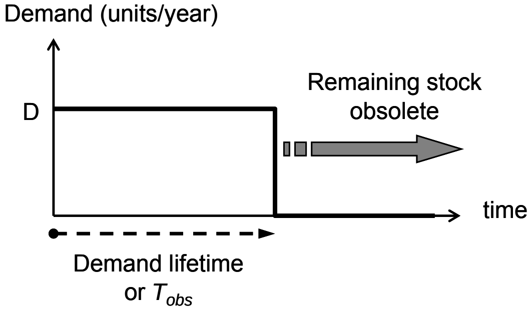


Figure 36. Obsolescence due to "Sudden Death" of the demand

As discussed in section 4.3, many external phenomena occurring non-deterministically can drive obsolescence. The time-to-obsolescence of the product, or lifetime of the demand, cannot be estimated without uncertainty, and should therefore be considered as a random variable. A lifetime of demand that is exponentially distributed has been proposed [146,148,149]. Figure 37 represents the probability density function of the random variable time-to-obsolescence T_{obs}.

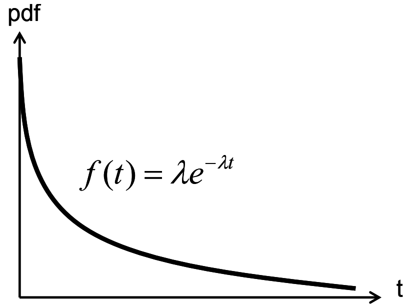


Figure 37. Probability density function for the time-to-obsolescence T_{obs}

Masters justifies the use of an exponential distribution by the fact that "[…] it models a constant obsolescence rate; that is, the case where the **age** of the item does not influence the probability of obsolescence during any subsequent interval." This statement is in agreement with the distinction made earlier between aging effects and obsolescence.

Based on an exponential distribution of parameter λ, similar metrics than those commonly used in reliability theory can be defined:

- the probability that the time-to-obsolescence will be smaller than a given period t is then simply expressed via the cumulative distribution function in Eq. 4.6.
- the mean-time-to-obsolescence is the inverse of the rate λ as shown in Eq. 4.7.

$$\Pr\{T_{obs} \leq t\} = 1 - \lambda e^{-\lambda t} \tag{4.6}$$

$$\langle T_{obs} \rangle = \frac{1}{\lambda} \tag{4.7}$$

4.4.2.3 Replacement and maintenance

In the previous approach, the demand for a given product was modeled and used as a proxy for obsolescence. Several operations research studies have also addressed the problem of finding optimal equipment replacement and maintenance strategies and have formulated models that capture the obsolescence of old equipment or components. Unlike the discontinuity characterizing the sudden death approach, replacement and maintenance studies typically model obsolescence as a gradual loss of value. For example, Rajagopalan [153] expressed the loss in salvage value over time (reflective of obsolescence) of an equipment unit with a negative exponential function, as shown in Eq. 4.8:

$$s(t_j) = \alpha e^{-\beta t_j} \tag{4.8}$$

At time $t_j>0$ the salvage value of the equipment unit is lower than the purchase cost α, as a result of obsolescence. The larger the value of the parameter β, the more severe the effects of obsolescence are. In the case of industrial plant maintenance, Borgonovo et al. [106] adopt a similar approach by assigning a residual value to old components, which they assume to "decrease continuously from the time of purchase according to an exponential law."

4.4.3 Obsolescence in Bibliometrics

4.4.3.1 Definition and methodologies

Bibliometrics is "the application of mathematical and statistical methods to books and other media of communication." [154]. An important topic of interest for researchers in this field is the obsolescence of scholarship, defined as the "phenomenon of the reduced use or decline in the use of information (on a certain topic) with time" [155]. Obsolescence in bibliometrics is essentially studied by observing how long a given publication keeps being cited. In other words, a document is considered obsolete when it is no longer cited frequently in other publications.

The analysis of literature obsolescence is typically conducted via either one of the two following approaches, as illustrated in Figure 38.

- The *synchronous* approach looks in the past, by examining the ages of the citations contained in a given publication or set of publications
- The *diachronous* approach looks in the future, by following a given source over time (publication or set of publications) and observing the number of times that said source is cited in future publications

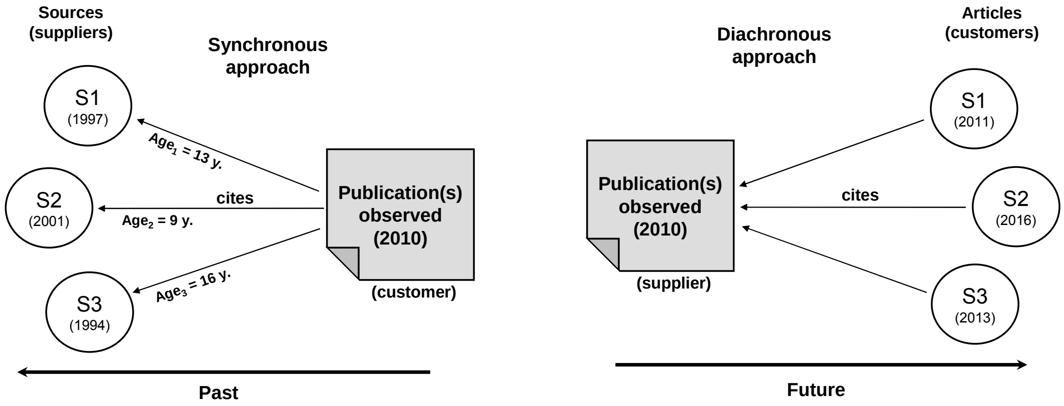


Figure 38. Synchronous approach (left) and diachronous approach (right)

Note that this dichotomy of approaches is consistent with the discussion regarding the two types of stakeholders that can experience obsolescence conducted in section 4.2. The synchronous method is a customer-centric approach of obsolescence, since a given set of publications (the “customer(s)”) collect information by referring to past scholarly articles (the sources or “suppliers”). If most references are recent, the literature can be considered to go obsolete quickly. Conversely, the diachronous method is a supplier-centric approach of obsolescence, since a given set of publications (the “supplier(s)”) constitutes a reference (i.e., provides information) for future scholarly articles. If in a given body of literature, the publications of interest are not cited for a long time (in other words, the demand fades out, as in section 4.4.2), the literature can be considered to go obsolete quickly.

According to Egghe and Rousseau [101], "[s]ynchronous studies are usually cheaper and easier to perform […] and […] synchronous and diachronous studies of the aging of scientific articles lead to the same conclusions, hence implying a preference for synchronous ones.".

4.4.3.2 Metrics of literature obsolescence

The bibibliometrics literature have proposed several metrics to capture the phenomenon of literature obsolescence that are discussed next.

- ***Citation age***

  In the case of synchronous studies, the citation age of a referred article is defined as the difference between the date of publication of the observed publication referring to this article and the date of publication of the article itself. Figure 38 shows examples of referred articles (S1, S2, S3) and their corresponding citation age. When conducting a synchronous study, the entire distribution of the citation ages (illustrated in Figure 39) provides insight regarding the level of obsolescence of the body of literature considered.

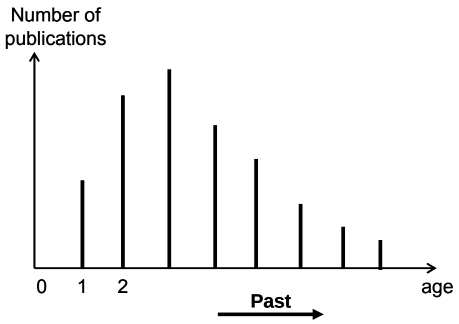


Figure 39: Citation age distribution

From the citation aging distribution, several statistical quantities are defined to study the phenomenon of obsolescence. Egghe and Rao [156] recall that early bibliometrics studies typically assumed a negative exponential form of the citation age distribution:

$$c(t) = c_0 e^{-c_0 t} \tag{4.9}$$

where *c(t)* represents the number of publications of age *t* years in the observed publication.

- ***Aging rate***

The aging function (or aging rate, or obsolescence rate) is generally defined as follows (if time is discrete):

$$a(t) = \frac{c(t+1)}{c(t)} \tag{4.10}$$

When *c(t)* follows an exponential distribution, *a(t)* is constant and is therefore often referred to as aging factor. Many bibliometrics studies of the obsolescence of literature typically focus on the aging function [101,156,157]. With a literature that goes obsolete, older publications are less and less cited, resulting in an aging rate that is smaller than 1.

- ***Literature half-life***

The concept of half-life in bibliometrics was first introduced in the late 1950's, by drawing an analogy between obsolescence of literature and the exponential decay of radioactive substances. The half-life $t_{1/2}$ traditionally represents the time needed for a substance to decay to half of its initial value. Burton and Kebler [158] formalized this concept for bibliometrics purposes by defining the half-life of a literature as the "time during which one-half of all the currently active literature was published". In other words, the half-life $t_{1/2}$ represents the median citation age, that is, 50% of the articles being cited have been published less than $t_{1/2}$ ago. The higher the citation half-time, the longer it takes for publications in a specific type of literature to become obsolete. When the citation distribution is exponential, the half-life is related to the mean citation age via Eq. 4.11.

$$t_{1/2} = \tau \ln 2 = \frac{\ln 2}{c_0} \tag{4.11}$$

Figure 40 shows values of the literature half-life for various disciplines.

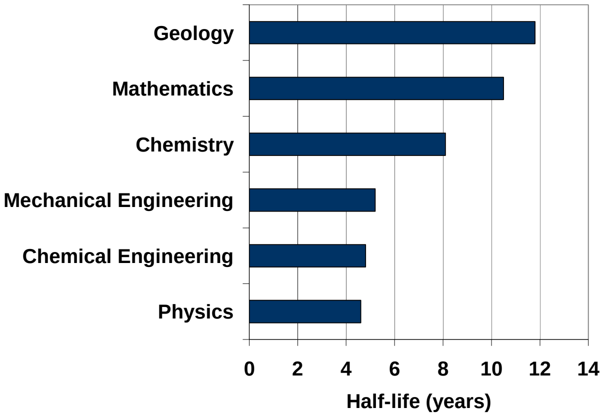


Figure 40: Half-life of different literatures (adapted from Burton and Kebler, 1960)

4.4.3.3 Obsolescence and supply volume

Later bibliometrics studies [159,101] acknowledge the impact of the growth of the volume of literature published on the obsolescence phenomenon. Specifically, two conflicting influences are identified by Egghe and Rousseau [101]:

- "The more a field grows, the more articles come into existence, acting as sources for references to the past, i.e., to articles published earlier.".
- "The faster a field grows the heavier the competition between "older" articles to get into the reference list of the new ones (the dilution effect)."

Gupta's synchronous citation study of *Physical Review* articles [159] accounts for the first effect, by normalizing the number of citations to *Physical Review* papers by the total number of articles published in *Physical Review* (i.e., the total "supply volume"). This example illustrates that obsolescence effects are more clearly analyzed when other external market effects (such as variation of number of suppliers or number of potential buyers over time) are removed. Special attention ought therefore to be paid to the proper normalization of the metrics that describe the obsolescence phenomenon.

4.4.4 Obsolescence in engineering

4.4.4.1 Obsolescence and product lifecycle curve

From a customer-centric perspective, obsolescence in engineering occurs when, **"**[a] part becomes obsolete when it is no longer manufactured" [160]. Sandborn and Myers [119] note that this is the inverse problem of the "Sudden Death" obsolescence situation encountered in Operational Research (as discussed in section 4.4.2), in which the inventory suddenly loses value as a result of a drop in demand. As mentioned in section 4.2, this challenge is significant for the Department of Defense, and is commonly referred to as Diminishing Manufacturing Sources and Material Shortages (DMSMS). For example, Sandborn [161] cites the case of a new sonar system developed by the U.S Navy for which more than 70% of the components were no longer manufactured when it was finally installed onboard ships in 2002. This problem not only affects hardware but also software applications [133] that are typically considered obsolete when “they are retired from use and taken off the market” [162] or when support or operating licenses are no longer provided [163].

Conversely, one traditional approach to define part obsolescence from a manufacturer or supplier point of view focuses on the evolution of the number of units sold over time (in other words, the demand for that specific product), as described by the Product Lifecycle curve. In this context, Cordero [164] discussed the apparent shortening of the product lifecycle curves over the last decades in some key industries [165], and linked it to an acceleration of the obsolescence of the associated products. This acceleration is particularly observed in the field of electronic components where new generations of microprocessors are introduced at an increasing rate, making the old generations obsolete faster and faster [166] (an example of technological obsolescence, as discussed in section 4.3.1).

In electronics, one commonly used standard of lifecycle curve is the American National Standards Institute (ANSI)/Electronic Industries Associations (EIA)-724 Product Life Cycle Data Model [167]. Using such a model, some authors such as Solomon et al. [168], Hatch [169] or Handfield and Pannesi [170] define obsolescence as the last phase occurring after the five traditional life cycle stages of a part (introduction, growth, maturity, decline, phase-out), as shown in Figure 41.

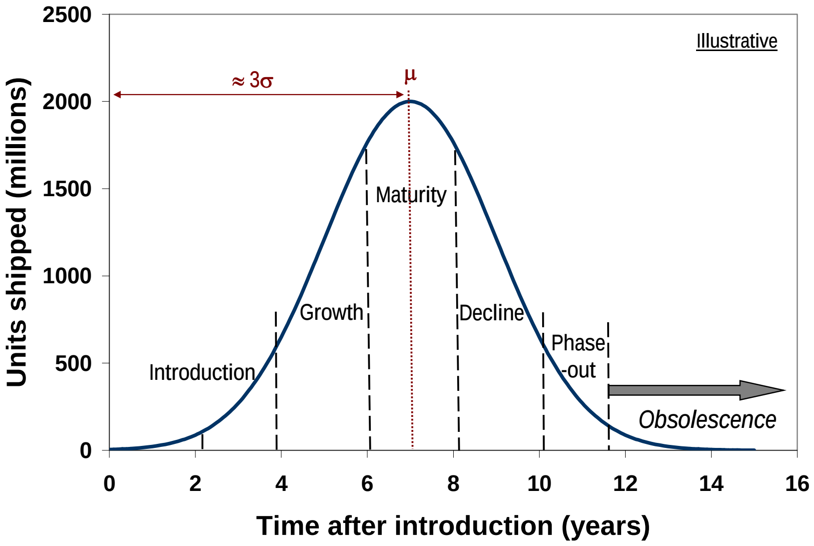


Figure 41: Traditional product lifecycle curve (adapted from Solomon et al. [168])

Focusing on component obsolescence, Solomon et al. [168] proposed a methodology to define the starting point of the obsolescence zone i.e. the onset of obsolescence T_{obs}, on a forecasted product lifecycle curve. A normal distribution that adequately fits the actual sales data (up to the date of the analysis) is first determined and characterized by its mean μ (corresponding to the peak sales date) and its standard deviation σ. The future zone of obsolescence is then deterministically defined by considering the interval expressed in Eq. 4.12:

$$\text{Zone of obsolescence} = [\mu + 2.5\sigma, \mu + 3.5\sigma] \tag{4.12}$$

The onset of obsolescence in this model is therefore $T_{obs} = \mu + 2.5\sigma$.

Note that the bell-shaped lifecycle curve only models one common behavior, but does not adequately represent many other possible situations [171]. As noted by Precht and Das [172], “[s]ome parts undergo a false start and die out, or may be associated with a niche market. Some parts may also be revitalized after the decline stage. Other possibilities can also arise due to various economic, social, and environmental occurrences."

In analyzing product lifecycle of computer systems, Greenstein and Wade [173] adopt a different definition of the on-set of product obsolescence T_{obs}, as "the first year that a product's installed base does not increase […], [that is] the first year in which retirements of the product are greater than the units sold." Unlike the previous approach, Greenstein and Wade's approach does not exclusively focus on the evolution on unit sales, but balances it with the unit retirements to reflect the actual "growth" of the usage of a given product.

4.4.4.2 New product release and time-to-obsolescence

Regardless of the degree of adoption of a product, another way to define the onset of obsolescence in the context of technological innovation is to consider the instant of release of a superior technology, an approach that is also customer-centric by nature. In the field of Information Technology (IT), Bradley and Dawson [133] analyzed the probability distribution of the time between two consecutive versions of a software for several popular software packages, and estimated it to follow a lognormal distribution. The authors argue that since the "expected time to re-release of any one piece of software is [found to be] 1160 calendar days", an old version of the software "would be considered obsolete around 1160 days later". In other words, provided a distribution of the instants of new software release is available (e.g., from statistical data analysis), the time-to-obsolescence can be defined probabilistically as the expected time of release of a new software version:

$$T_{obs} = \langle T_{renew} \rangle \tag{4.13}$$

This approach implicitly assumes that every new innovation will succeed in penetrating the market enough to change the users' expectations, thus rendering obsolete previous versions of a product. As discussed in section 4.3.2.1, this may or not may be the case, depending on other circumstances such as network externalities. One important aspect of the Bradley and Dawson model is the modeling of the time-to-obsolescence in a non-deterministic fashion. Recent studies addressing the problem of obsolescence in engineering have now moved forward in that direction, by incorporating a probabilistic dimension of obsolescence in one form or another [174], as will be proposed in the next chapter.

4.4.4.3 Mitigation strategies

In economics, operational research and bibliometrics, obsolescence studies have almost exclusively focused on the modeling of the phenomenon of obsolescence. Conversely, in addition to the modeling approaches presented previously in this section, much of the engineering literature investigates practical mitigation strategies to limit the penalties resulting from component obsolescence. Those approaches, discussed by Stogdill [175], Solomon et al. [168], Howard [176], Singh and Sandborn [97] typically include: lifetime buys (purchase and storage a stock of parts in order to last during the entire lifetime of a system), part replacement (use of components similar to the obsolete ones), reliance on aftermarket sources, redesign of subsystems to host newer components, reclamation (use of salvaged components from retired products), uprating (use of components outside of their specification limits; see Wright, et al. [177]), etc. Many of those strategies only constitute short-term solutions [176] and are often particularly costly as they are reactive by essence [178], since the issue of obsolescence is addressed only after it has occurred. As a result, more proactive methods that would be more beneficial (i.e., less costly) in the long term are explored, such as the careful and anticipatory planning of product redesigns in order to minimize the total lifecycle costs [97]. Note that with such approaches, the forecasting of obsolescence by adequately modeling the time-to-obsolescence T_{obs} (as discussed throughout this chapter) plays a crucial part.

4.5 Summary

The purpose of this chapter was to provide conceptual contributions to the understanding of the phenomenon of obsolescence that affect many assets and products in modern society. First, this chapter discussed the key concepts inherent to the issue of obsolescence, by highlighting that – unlike other product characteristics that only depend on how the product operates (such as performance or reliability) – obsolescence involves *the relationship* of a stakeholder to the product over time, in a given environment. Specifically, the following definition of product obsolescence was proposed:

Obsolescence is the decline of value of a product over time, due to a change in the stakeholder's expectations resulting from exogenous events.

Two categories of stakeholders typically encounter obsolescence: 1) suppliers (or manufacturers), for which obsolescence may manifest itself through a drop in demand, and 2) users (or customers) who will favor newer or other solutions to meet their needs. The root causes of the obsolescence phenomenon were then discussed and four main drivers were identified: technological innovation, network externalities, regulatory changes and need disappearance. This chapter then examined how obsolescence has been traditionally approached and modeled in various disciplines, namely in economics, operations research, bibliometrics and engineering (summarized in Table 8).

Through this review, two main angles of study emerged:

1. **The decline-focused perspective**. In such approaches, one is concerned with the rate of decline of product value that characterizes the obsolescence phenomenon, that is, the degree of obsolescence. Obsolescence is then often considered to be pure depreciation and is assumed to take effect as soon as an asset is produced. It is the approach adopted in economics and in operation research studies dealing with equipment replacement and maintenance. In a similar fashion, the decline in use in bibliometrics is conceived as a gradual phenomenon that starts as soon a scholarly article is published (equivalent to the "production"). Several models of decline have been proposed, such as functional forms parameterized by straight-line, geometric or negative exponential rates. Ultimately, the purpose of such methods is to quantify the extent to which an item is less valuable to the user.

2. **The instant-focused perspective**. In such approaches, one is concerned with the instant at which obsolescence starts, in other words, the onset of obsolescence. This event generally occurs during the lifetime of a product, due to external changes such as technological innovation. It is the approach adopted in operation research studies dealing with inventory management (through the assumption of

> "sudden death" of demand) or part obsolescence management in engineering. Rather than aiming at characterizing the amplitude of the decline in value, the purpose of such methods is to define a time-to-obsolescence T_{obs} after which obsolescence is considered to be established. Depending on the discipline, various metrics have been proposed: time of release of superior alternatives, time defined from the peak usage instant (from the product lifecycle curves), median design age (from the "half-life" of bibliometrics), etc. The proposed formulations of a time-to-obsolescence T_{obs} have been both deterministic (from the forecasted product lifecycle for example), as well as non-deterministic, through the use of probability density functions (e.g., exponential or lognormal distributions).

While each discipline has focused on one or the other formulation adapted to its field of applications, a complete description of the obsolescence phenomenon is in many cases likely to require both the characterization of a time-to-obsolescence and the selection of a pattern modeling the decline of value that ensues. The discussion conducted in this chapter has thus laid the ground for the stochastic model of on-orbit obsolescence of space systems that is developed in the next chapter.

Table 8. Views on obsolescence among different disciplines

Discipline	Manifestation of obsolescence	Metrics used	Focus	Models	References
Economics	Depreciation	Price	Decline	Straight-line Geometric	Fraumeni, 1997 [143] Hulten and Wykoff, 1980 [144] BEA, 2010 [145]
Operations Research	Drop of demand	Number of units sold	Instant	Exponentially distributed	Masters, 1991 [149] van Delft and Vial, 1996 [146] David and Greenshtein, 1996 [148]
	Decline in salvage value	Price	Decline	Negative exponential	Rajagopalan, 1998 [153] Borgonovo et al., 2000 [106]
Bibliometrics	Aging of literature	Aging factor	Decline	Exponential	Brookes, 1970 [157] Egghe and Rao, 1992 [156] Egghe and Rousseau, 2000 [101]
		Half-life	Instant	Median of citation distribution (exponential)	Burton and Kebler, 1960 [158]
Engineering	Product demand	Shipments	Instant	Deterministic from “normal” product lifecycle curve	Solomon et al., 2000 [160] Hatch, 2000 [169] Handfield and Pannesi, 1994 [170]
		Shipments - Retirements	Instant	Deterministic from product lifecycle curve	Greenstein and Wade, 1998 [173]
	Discontinuation of production	Procurement lifetime	Instant	Probabilistic	Sandborn et al., 2010 [174]
	Release of superior design	Time of new release	Instant	Probabilistic from distribution of time of new release	Bradley and Dawson, 1998 [133]

CHAPTER 5

RISK OF ON-ORBIT OBSOLESCENCE: NOVEL FRAMEWORK, STOCHASTIC MODELING AND IMPLICATIONS

> **"A horse never runs so ~~fast~~ as when he has other horses to catch up and outpace"**
> [slow]
>
> (Attributed to Ovid, Roman author 43 BC – AD 17/18)

5.1 Introduction

As discussed in section 1.1, the United States Government Accountability Office has 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 the GAO [22,25]. These reasons include budget constraints, schedule and organizational considerations, requirements creep, 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 [22]

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

This chapter focuses on the risk of on-orbit obsolescence rationale for DOD's position regarding the inclusion of low TRL in acquisition programs. The objective here 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.

This chapter is organized as follows. First, the implications of obsolescence in system design are briefly presented in section 5.2, and the specificities of space systems are highlighted in section 5.3 to lead to the formulation of the concept of "risk of on-orbit obsolescence". In sections 5.4 and 5.5, the analytical background upon which this chapter is based is introduced, with a brief overview of Markov Chains and Monte-Carlo simulations; these constitute the analytical underpinnings of the quantitative analysis of the risk of obsolescence. Section 5.6 introduces a stochastic framework and models for analyzing the risk of on-orbit obsolescence, by formulating Markov models of obsolescence and technology maturation. In section 5.7, Monte-Carlo simulations of the models are run and the results obtained are analyzed, with a focus 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. Finally, this chapter discusses 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 provides space organizations with guidelines to trade the Risk of On-Orbit Obsolescence against the time of capability delivery.

5.2 Facing the consequences of obsolescence or designing for obsolescence?

Chapter 4 discussed the causes and modeling approaches of system obsolescence. It is now important to recognize that 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 as discussed in section 4.4.4.3 (through for example replacements or upgrades of parts that have become obsolete [175]) 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.” [161]

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. This chapter proposes 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 chapter, 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.

The following section focuses particularly on space systems, and briefly discusses why some of the specificities of these systems make the issue of obsolescence more critical and challenging to address.

5.3 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 [179], 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 [180], 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 value 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 discussed in Chapter 4, 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" [181]. While this case illustrates a form of logistical obsolescence (where procurement of parts becomes impossible due to discontinuation of production [163]), 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. This chapter proposes 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. The 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.

The following section provides the background information on Markov chains and Monte Carlo simulation, before the models and analyses are discussed in section 5.6.

5.4 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 $\{ X_n \mid n = 0, 1, \ldots \}$ 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. (5.1).

$$\Pr\{X_{n+1} = j \mid X_n = i, X_{n-1} = i_{n-1}, \ldots, X_0 = i_0\} = \Pr\{X_{n+1} = j \mid X_n = i\} = p_{ij} \qquad (5.1)$$

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. Equation 5.1 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. Figure 42 shows an example of a transition matrix for a system with four states.

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

Figure 42. 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 Figure 43.

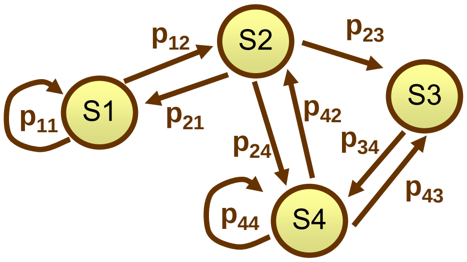


Figure 43. Typical transition graph for a Markov chain

Markov chains have been used in a wide variety of contexts and for different applications in health care [182], economic valuation [183], and reliability analysis [184] to name a few. More information about Markov chains can be found several textbooks including [185, 186, 187].

5.5 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 [90]. Here, 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 are conducted. These Markov chains are discussed in section 5.6. The probabilistic nature of these models is directly used to feed the Monte-Carlo simulations. In this work, 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. This work considers the evolution of the risk of on-orbit obsolescence over time, and therefore defines a time-horizon for the analysis that will be denoted by τ_{ops}. The Markov models stop running when the time-horizon is reached, i.e., when t = τ_{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.

5.6 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.

5.6.1 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. Each consecutive obsolescence state thus represents a "drop" in value due to obsolescence. This state representation constitute a flexible combination between the "instant-focused" perspective (where the onset of obsolescence is the instant of the first transition to the minor Obsolescence) and the "decline-focused" perspective (that can be modeled by as many different obsolescence states as required), as discussed in Chapter 4.

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. (5.2).

$$P = \begin{bmatrix} p_{11} & p_{12} & p_{13} \\ 0 & p_{22} & p_{23} \\ 0 & 0 & p_{33} \end{bmatrix} \tag{5.2}$$

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). It is assumed 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 Figure 44.

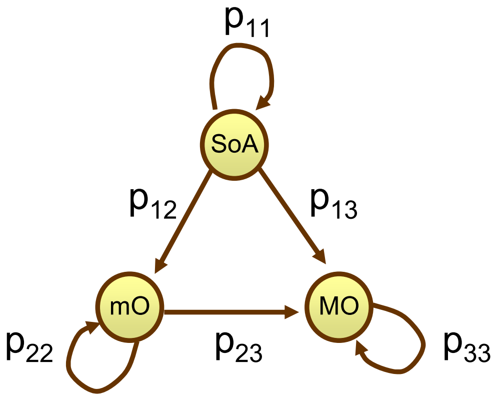


Figure 44. State representation of the obsolescence model

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, a simple case of a spacecraft with a single instrument was considered). Among the set of spacecraft components that are subject to obsolescence, electronic parts (as mentioned in subsection 4.4.4.1.) 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 [188]. 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 study.

5.6.2 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). The notion of "system-TRL" will be used to represent the level of maturity of the entire spacecraft, as defined in section 2.6 by a weighted average of all its components' TRLs. 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.

Section 2.6 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. Here, the model developed in section 2.6 is applied recursively to estimate the time needed to transition from a given system-TRL value to the consecutive one. Table 9 summarizes the values obtained when conducting this process. For example, historical data shows 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. The difference (78 – 61 = 17 months) was then used 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 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.

Table 9. 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	$p_{\Delta TRL5} = 0.0438$
5	78.6	17.4	$p_{\Delta TRL6} = 0.0559$
6	61.2	13.6	$p_{\Delta TRL7} = 0.0712$
7	47.6	10.5	$p_{\Delta TRL8} = 0.0905$
8	37.1	8.2	$p_{\Delta TRL9} = 0.1218$
9	28.9	6.4	$p_{\Delta TRL9+} = 0.1448$
9+	22.5	N/A	N/A

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. (5.3), since a system can only transition to the consecutive TRL or stay at the current one.

$$M = \begin{bmatrix} 1-p_{\Delta TRL_5} & p_{\Delta TRL_5} & 0 & 0 & 0 & 0 & 0 \\ 0 & 1-p_{\Delta TRL_6} & p_{\Delta TRL_6} & 0 & 0 & 0 & 0 \\ 0 & 0 & 1-p_{\Delta TRL_7} & p_{\Delta TRL_7} & 0 & 0 & 0 \\ 0 & 0 & 0 & 1-p_{\Delta TRL_8} & p_{\Delta TRL_8} & 0 & 0 \\ 0 & 0 & 0 & 0 & 1-p_{\Delta TRL_9} & p_{\Delta TRL_9} & 0 \\ 0 & 0 & 0 & 0 & 0 & 1-p_{\Delta TRL_{9+}} & p_{\Delta TRL_{9+}} \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \tag{5.3}$$

The state diagram of this Markov model is shown in Figure 45.

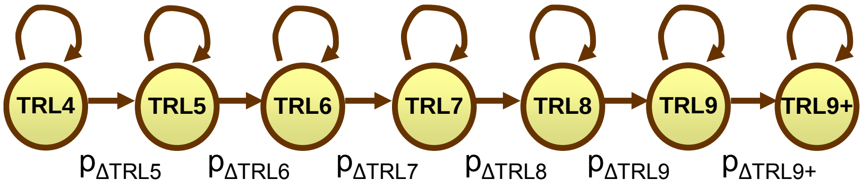


Figure 45. State representation of the technology maturity model

5.6.3 *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 9. 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 $TRL_{ini} = 7$ [22].

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 the 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 [49]. 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.

5.6.4 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 this analysis is its design lifetime, which is denoted 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. (5.4):

For a given initial TRL_i,
$$t^* = \max\left[0, T_{life} - FTD(TRL_i)\right] \tag{5.4}$$

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 $Age = 0^+$).

This chapter will 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 Figure 46.

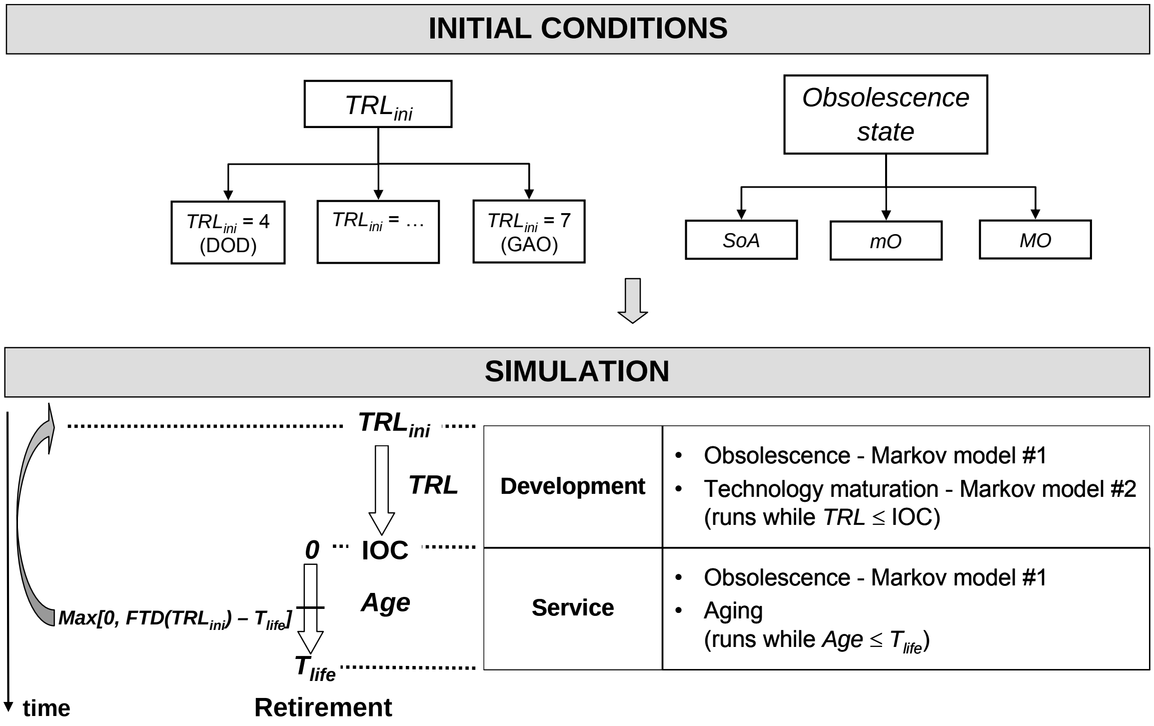


Figure 46. Representation of the simulation for one single series of spacecraft

5.7 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 time-horizon τ_{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 [189]. 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 subsections 5.7.2 and 5.7.3.

5.7.1 Obsolescence maps

Following the formulation of the concept of Risk of On-Orbit Obsolescence in section 5.3, 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, the time spent by the spacecraft is thus "observed" 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, an "obsolescence map" is populated, as represented on Figure 47. 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 τ_{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.

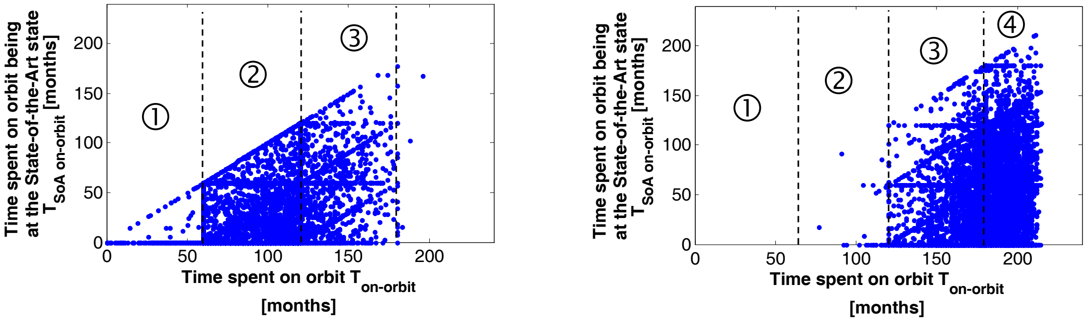


Figure 47. Obsolescence map
for T_{life} = 5 years and TRL_{ini} = 4 (left), or TRL_{ini} = 7 (right)

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 Figure 47 before delving 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 τ_{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 this 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 ≥ 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 the left plot of Figure 47 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 the right plot of Figure 47 ($TRL_{ini} = 7$), compared to the left plot of Figure 47 ($TRL_{ini} = 4$).

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.

5.7.2 Static Risk of On-Orbit Obsolescence (SRO)

The static risk of on-orbit obsolescence (SRO) is defined 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. (5.5).

$$SRO = E\left[1 - \frac{T_{SoA-on-orbit}}{T_{on-orbit}}\right] \tag{5.5}$$

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. Figure 48 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 (this statement will be revisited in subsection 5.7.3.2 and the specific context in which the initial technology maturity may influence the risk of obsolescence will be discussed).

- **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.

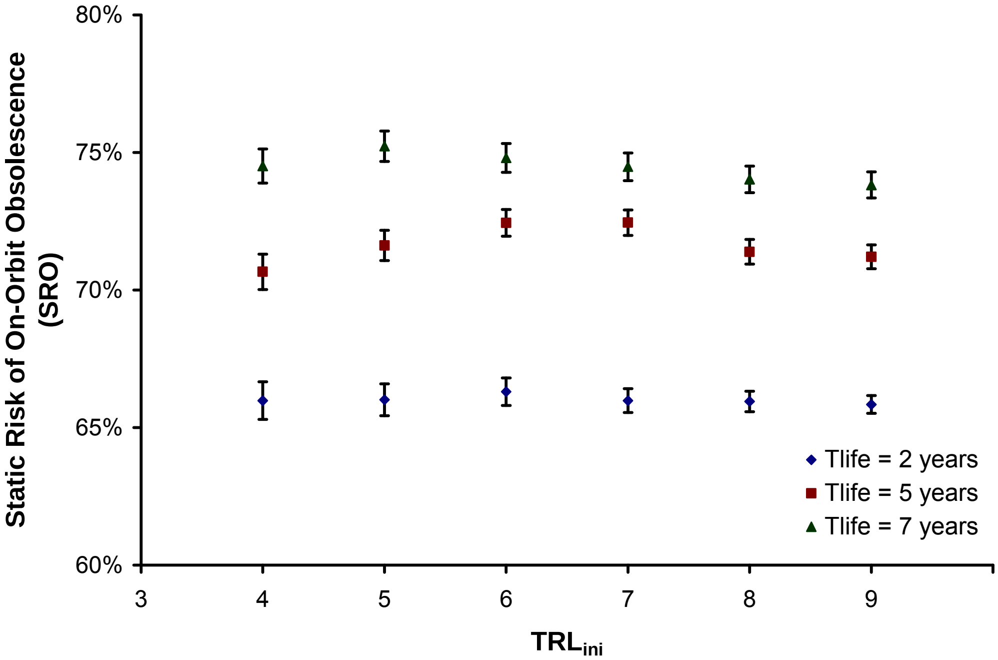


Figure 48. Static Risk of On-Orbit Obsolescence for the various values of the model parameters and corresponding 95% confidence intervals

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

$$\varepsilon = \frac{z_{\alpha/2}\sigma}{\sqrt{n}} \tag{5.6}$$

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 σ is unknown, the sample standard deviation s obtained by the Monte-Carlo simulation is used to compute the error ε on the estimate [190]. For 10,000 Monte-Carlo cases, Table 10 shows the values of s and the corresponding error ε on the SRO for the various settings of T_{life} and TRL_{ini}.

Table 10. Standard deviation s of ($1 - T_{SoAon\text{-}orbit} / T_{on\text{-}orbit}$) and error ε 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
	ε	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
	ε	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
	ε	0.006172	0.005515	0.005253	0.005037	0.004824	0.004735

In all cases, the error on the estimate remains less than 1 percentage point. The error bars corresponding to the 95% confidence intervals defined by SRO ± ε are plotted on Figure 48. 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 [191] 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.

5.7.3 Two dynamic views of the risk of on-orbit obsolescence

Two additional measures for the risk of on-orbit obsolescence based on instantaneous quantities (i.e., defined at every instant of time) are now proposed, 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, it is essential to emphasize the importance of precisely specifying the temporal mindset in which one operates. Section 3.6.2 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).

5.7.3.1 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), this section will 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:

$$LRO(t') = \Pr\{Obsolete\}(t') \tag{5.7}$$

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 Figure 49.

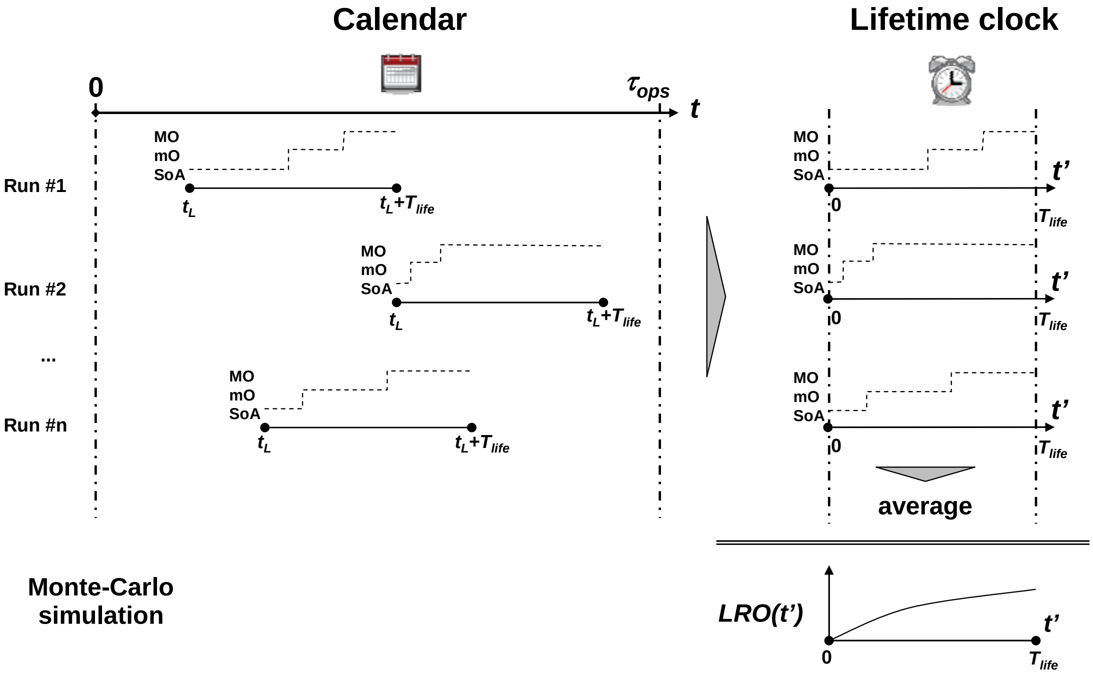


Figure 49. Illustration of the calculation process of the Lifetime Risk of On-Orbit Obsolescence

Figure 50 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.

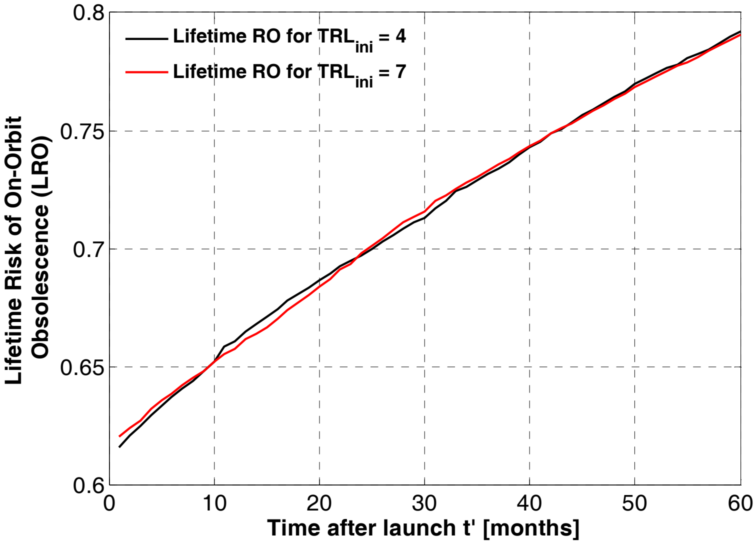
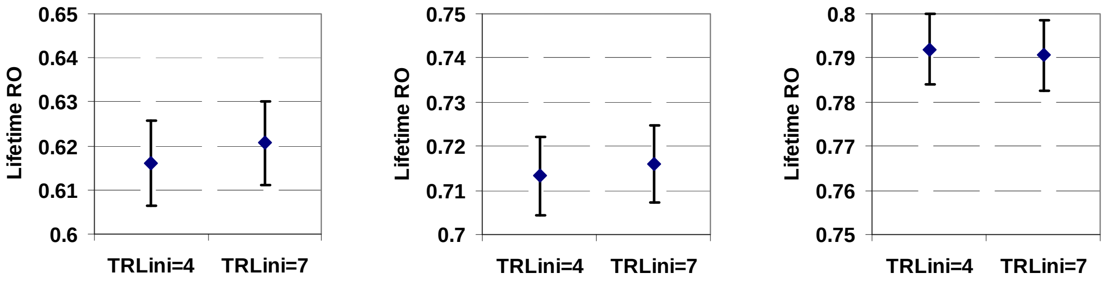


Figure 50. Lifetime Risk of On-Orbit Obsolescence for TRL_{ini} = 4 and TRL_{ini} = 7 (T_{life} = 5 years)

Figure 51 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.



t' = 1 month after launch t' = 30 months after launch t' = 60 months after launch
($t' = T_{life}$)

Figure 51. 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)

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[§§§]. 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.

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. The next section introduces a second dynamic risk measure, the "Calendar Risk of On-Orbit Obsolescence" (CRO).

[§§§] The mode of production is for example different for a one-of-a-kind scientific satellite than for a production-line defense satellite.

5.7.3.2 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), this section adopts 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, the "Calendar Risk of On-Orbit Obsolescence" (CRO) is defined as follows:

$$CRO(t) = \Pr\{obsolete \mid on-orbit\}(t) = \frac{\Pr\{obsolete\ AND\ on-orbit\}(t)}{\Pr\{on-orbit\}(t)} \tag{5.8}$$

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 Figure 52.

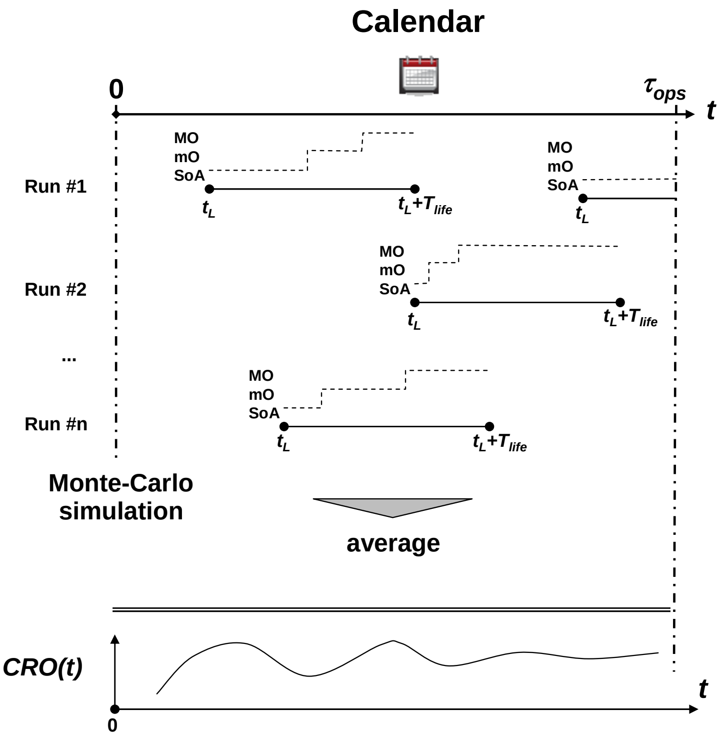


Figure 52. Illustration of the calculation process of the Calendar Risk of On-Orbit Obsolescence

Using a design lifetime T_{life} = 5 years, Figure 53 represents 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 (left of Figure 53). 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 subsection 5.7.3.1, 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 at a given calendar date after the start of their development than high TRL systems.

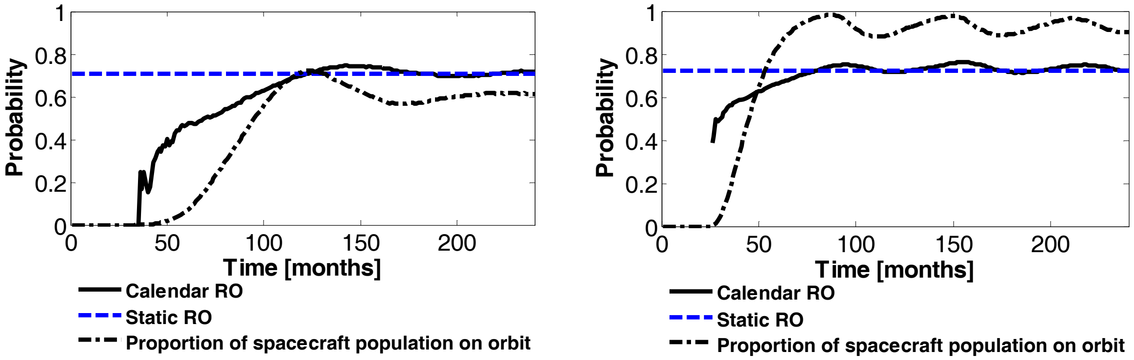


Figure 53. Calendar Risk of On-Orbit Obsolescence for T_{life} = 5 years and TRL_{ini} = 4 (left) vs. TRL_{ini} = 7 (right)

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. Figure 54 shows 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, the right plot of Figure 54 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.

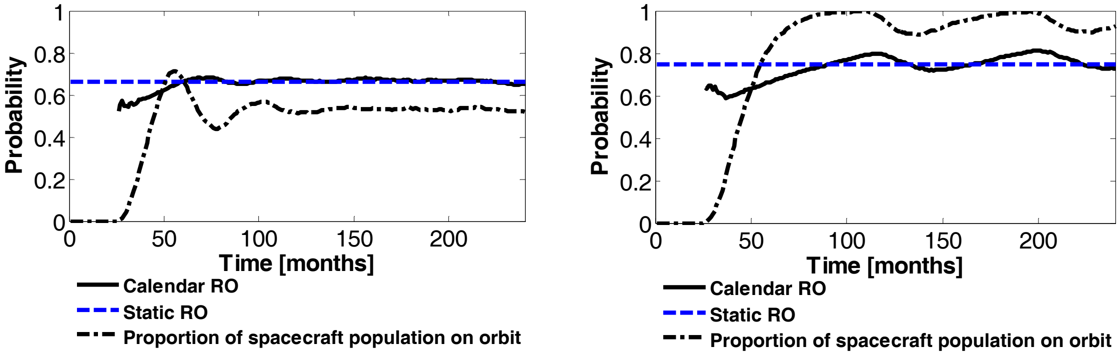


Figure 54. Calendar Risk of On-Orbit Obsolescence for TRL_{ini} = 7 and T_{life} = 2 years (left) vs. T_{life} = 7 years (right)

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, as discussed in section 3.6.2). 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 the 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 (as discussed in sections 2.6 and 3.5.1).

- 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 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, the time required to deliver a spacecraft is quantified based on the initial technology maturity TRL_{ini}.

5.7.4 Time-to-Orbit or time of first delivery of capability

Another effect of including more mature technologies in space systems was previously alluded to: 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 chapter 2, has become crucial as increasingly more resources are invested to develop an "Operationally Responsive Space". The Time-to-Orbit is denoted by $\tau_{to\text{-}orbit}$, 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 Figure 55, 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).

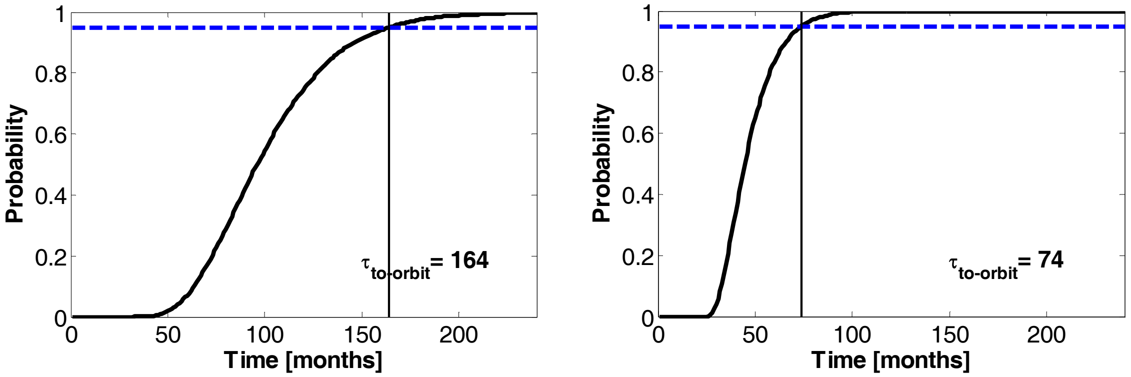


Figure 55. First delivery to orbit for T_{life} = 5 years and TRL_{ini} = 4 (left) vs. TRL_{ini} = 7 (right)

Table 11 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}.

Table 11. 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

5.7.5 *Obsolescence-responsiveness plot*

The results presented previously in 5.7.3.2 and 5.7.4 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 Figure 56: 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).

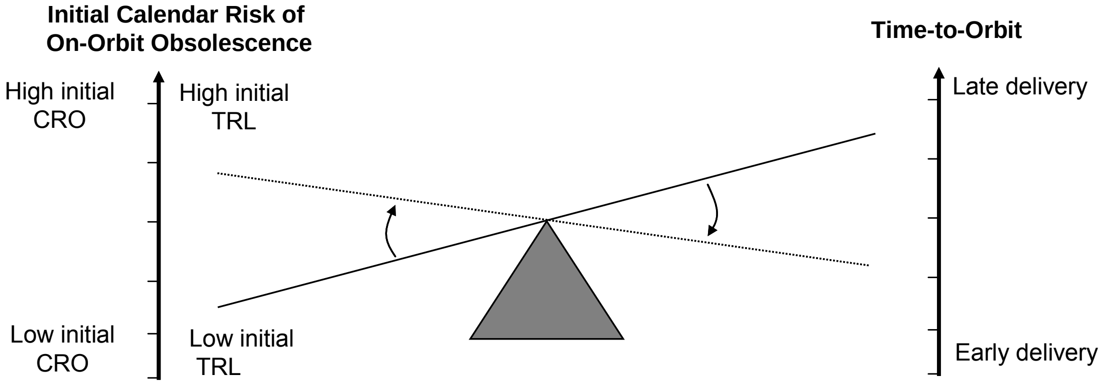


Figure 56. Illustration of the trade-off between initial CRO and time of first delivery of capability

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 chapter 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. Figure 57 provides an example of such a plot for a CRO three years after the start of the spacecraft development[****].

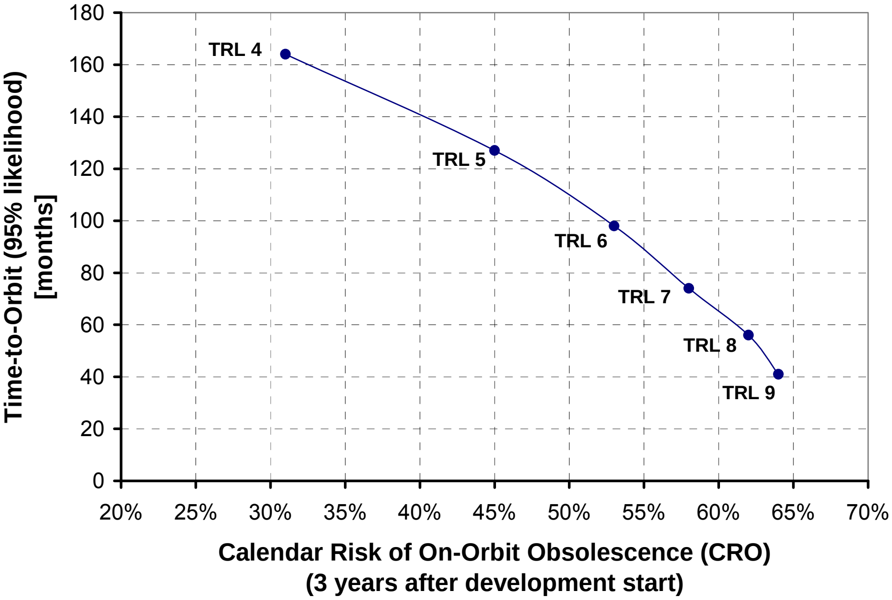


Figure 57. Example of an Obsolescence-Responsiveness plot

- Figure 57 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

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[****] 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.

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 less than 50 % chance of being obsolete three years after the development starts, then system-TRL less than 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 (Figure 57) 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. (31)), 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.

5.8 Summary

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 TRL ≥ 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 was referred to as the “Risk of On-Orbit Obsolescence”.

In this chapter, a stochastic model of Risk of On-Orbit Obsolescence based on two Markov models was developed: 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, this chapter 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 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.

In section 2.6, the influence of technology maturity on schedule slippage was analyzed at the system-level, through the definition of a system-TRL for the entire spacecraft. Similarly, the approach undertaken in this chapter to model the risk of on-orbit obsolescence was by construction system-centric: each state of the Markov chain represented the level of obsolescence of the entire spacecraft.

The next chapter will propose an integrated modeling framework that:

1) goes beyond the initial system-centric evaluation of obsolescence previously presented, by modeling the obsolescence phenomenon at the instrument (or subsystem) level
2) connects this new instrument-centric obsolescence model to the model of spacecraft Time-to-Delivery based on the idea of spacecraft portfolio presented in Chapter 3. The resulting framework provides a powerful capability to simultaneously explore the impact of design decisions on spacecraft schedule, on-orbit obsolescence, and utility delivered over time.

CHAPTER 6

INTEGRATED STOCHASTIC ANALYSES: SPACECRAFT DELIVERY AND ON-ORBIT OBSOLESCENCE

"The sources of poetry are in the spirit seeking completeness."

Muriel Rukeyser, American poet

6.1 Introduction

Chapter 2 discussed the importance of responsiveness for the space industry, and presented several "levers of space responsiveness", or means to influence the schedule of space systems (reducing the extent and likelihood of schedule slippage and/or improving the overall responsiveness). Chapter 3 focused on the design-centric levers of responsiveness and introduced a stochastic model of spacecraft time-to-delivery by conceiving of a spacecraft as a portfolio of instruments or technologies. The implications of the choice of the portfolio characteristics (e.g., number of instruments, various instrument TRLs) on the spacecraft delivery schedule and the cumulative utility delivered by the spacecraft were investigated. Once the spacecraft is on orbit, it is exposed to another type of "temporal risk", namely the risk of on-orbit obsolescence. After a general overview of the issue of system obsolescence conducted in Chapter 4 and the presentation of various approaches to model this phenomenon, a stochastic model of spacecraft obsolescence at the system-level was formulated in Chapter 5, and the impact of technology maturity (via the average system-TRL) and design lifetime T_{life} on the risk of on-orbit obsolescence was explored. Figure 58 illustrates how design choices such as spacecraft portfolio size, various TRLs and design lifetime T_{life}, can influence the time-to-delivery and time-to-obsolescence of the spacecraft, ultimately impacting the cumulative utility delivered by the spacecraft over its actual lifetime (in a clock-based design mindset) and/or over a given time horizon of interest (in a calendar-based mindset).

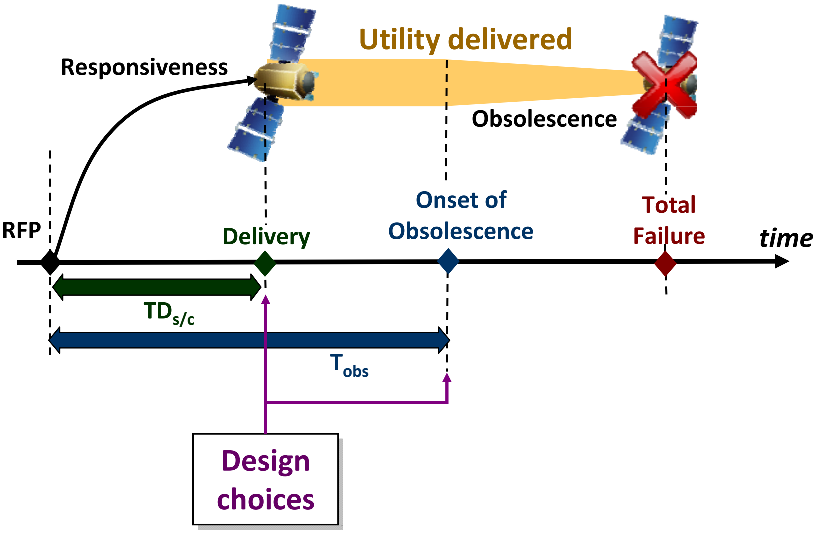


Figure 58. Spacecraft lifecycle and the impact of design choices on time-to-delivery and time-to-obsolescence

This chapter proposes to connect together the two main models presented in Chapter 3 and 5 and to analyze *jointly* the impact of design choices (materialized by the selection of portfolio characteristics) on both the time-to-delivery $TD_{s/c}$ and time-to-obsolescence T_{obs} of the spacecraft. The result is an integrated framework that should help inform decisions made during the design of a spacecraft (or series of spacecraft) when timeliness and utility delivered are important objectives being considered.

To do so, the model of spacecraft time-to-delivery presented in Chapter 3 is first refined in section 6.2 by adopting a local approach to model the instruments delivery schedule that magnifies the progression of the technology maturation process. This refined model constitutes the "development module" of the integrated framework. In section 6.3, an obsolescence model at the instrument (or subsystem) level is formulated, and is made compatible with the spacecraft portfolio approach developed in Chapter 3. This obsolescence model combined with a simple probabilistic model of failure and a spacecraft replacement strategy (presented in section 6.4) constitutes the "operations module" of the integrated framework. The full framework, that is stochastic and state-based by construction, is presented in section 6.5. Finally, in section 6.6, the main results produced by the integrated framework are discussed, through the description of utility profiles obtained for single spacecraft as well as series of spacecraft, and the analysis of two example mission scenarios (science and defense missions).

6.2 Development module: model of spacecraft Time-to-Delivery

Chapter 3 presented a probabilistic model of spacecraft Time-to-Delivery that was formulated around the concept of spacecraft portfolio. This model of spacecraft Time-to-Delivery assumed that the delivery schedule of a spacecraft follows three main phases that are conducted sequentially: the instruments development phase, the integration and testing phase, and the shipping and launch operations phase. The duration of each phase was treated as random variable, whose probability density function was assumed to be lognormal, with parameters indexed by the spacecraft portfolio characteristics (e.g., instruments TRLs, size) and derived from historical data. By adding the three intermediate random variables calculated in the model of Instruments Delivery Schedule

(IDS), the model of spacecraft Integration & Testing time, and the model of Shipping time, the final random variable of spacecraft Time-to-Delivery was obtained. The following section proposes a refinement of the model of Instruments Delivery Schedule (IDS). In section 3.4.1, the Instruments Delivery Schedule was modeled according to a "global approach": a probability distribution of the time TD_i elapsed between the development start and the instrument delivery was defined as a function of the initial instrument TRL_{ini}. Figure 59 illustrates how the Time-to-Delivery TD_i of a portfolio instrument *i* was directly modeled by one single lognormal distribution.

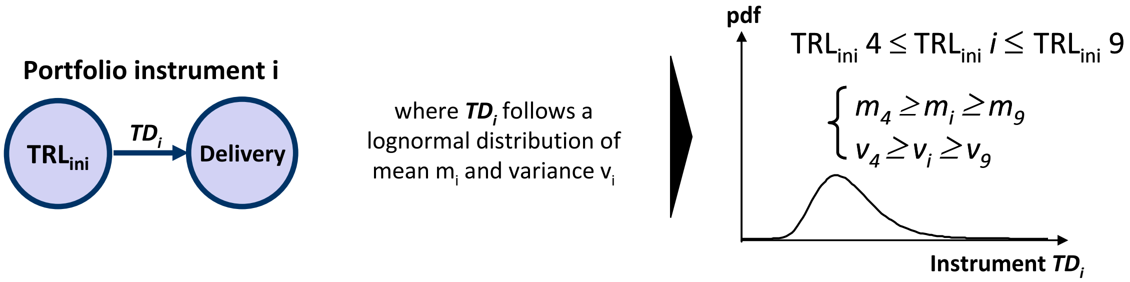


Figure 59. Global approach of instrument time-to-delivery (notional)

6.2.1 *Local approach of technology maturation and instrument development*

This section proposes an alternate approach to model the instrument time-to-delivery, aligned with the state-space representation of technology maturation proposed in Chapter 5. In this "local approach", the maturation of the main technology characterizing instrument *i* is followed step-by-step, by modeling the successive Technology Readiness Levels reached by technology *i*, from the initial TRL at the development start. Each transition from one TRL to the next is captured by a random variable that follows a given distribution.

For example, assume that the time to transition from TRL k to TRL (k+1) follows an exponential distribution of parameter λ_k, whose value can be derived from historical data (as presented in Chapter 5):

$$f(T_{TRL(k)\rightarrow TRL(k+1)}) = \lambda_k e^{-\lambda_k T_{TRL(k)\rightarrow TRL(k+1)}} \tag{6.1}$$

This “local” approach, represented in Figure 60, provides more resolution and flexibility to model the technology maturation process. For example, specific distributions can be used to model the difficult transitions from TRL 4 to TRL 6, which have often been discussed, sometimes under the term “TRL gap” or “TRL Valley of Death” [192,193,194]. In addition, unlike the global approach, this local approach allows the explicit modeling of returns to lower TRL values (e.g., when technical problems are identified and things have to be “redesigned”). Indeed, the “linear path” (from TRL 1 straight to TRL 9) is common for critical mission subsystems but may not occur every time (especially around TRL 7, as described by Mankins [195]). Similarly, Cornford and Sarsfield state that “few development efforts move sequentially along the TRL continuum” [196]. In that case, the local approach gives the flexibility to rearrange the TRL states and transitions to reflect the path taken by the technology maturation process for the technology considered.

Note also a final refinement visible in Figure 60: an instrument that has never flown on an actual mission jumps directly from TRL 8 to the final delivery state, once its development is complete. If the instrument has been flown on previous missions (i.e., the instrument has some "heritage"), it starts at a TRL 9 and transitions to the final delivery state once the necessary adjustments to its design have been performed.

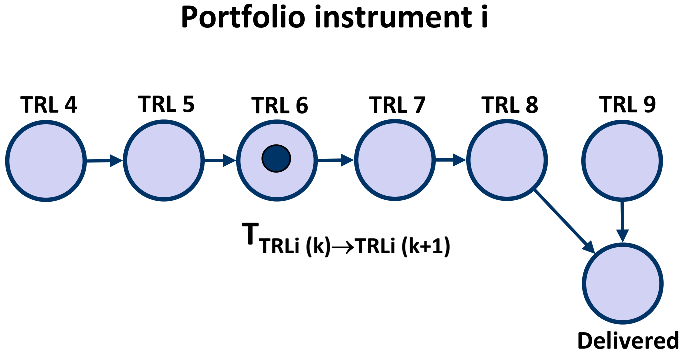


Figure 60. Local approach of instrument time-to-delivery

The final Time-to-Delivery of instrument *i* can then be computed by summing the consecutive transition times from the initial TRL to the final delivery state, as expressed in Eq. 6.2:

$$TD_i = \sum_{TRL_i = TRL_{ini}}^{TRL_i = 8 \text{ or } 9} T_{TRL_i = k \rightarrow TRL_i = k+1} \qquad (6.2)$$

6.2.2 Spacecraft Integration & Testing

Once all the instruments and the bus have been delivered, the integration and testing of the spacecraft can start. The duration of this phase is captured by the random variable T_{int} that follows a specific lognormal distribution depending on the spacecraft portfolio size (number of instruments), as discussed in section 3.4.2.

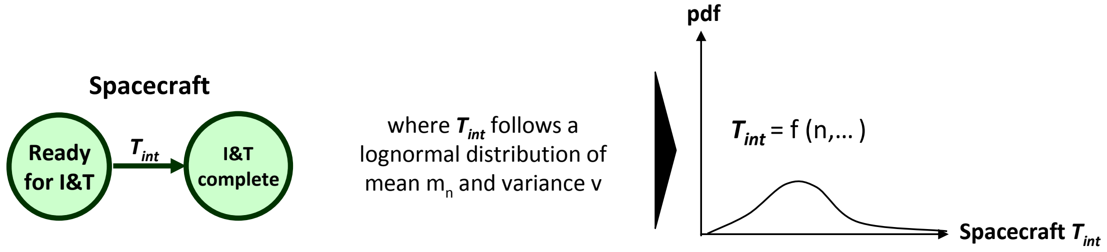


Figure 61. Model of spacecraft Integration & Testing duration (notional)

Recall the functional form of the probability density function of the random variable T_{int} discussed in section 3.4.2:

For a given portfolio size *n*,

$$f(T_{int}, m_n, v) = \frac{1}{T_{int}\sigma_n\sqrt{2\pi}} e^{-\frac{(\ln(T_{int})-\mu_n)^2}{2\sigma_n^2}} \qquad (6.3)$$

$$\text{with} \quad \begin{cases} \mu_n = \ln\left(\dfrac{m_n^2}{\sqrt{v+m_n^2}}\right) \\ \sigma_n = \sqrt{\ln\left(\dfrac{v}{m_n^2}+1\right)} \end{cases} \qquad \text{and} \quad \begin{cases} m_n = a\cdot n + b \\ v = c \end{cases} \qquad (6.4)$$

6.2.3 Spacecraft shipping and launch operations

Once the instruments and the bus have been integrated and tested, the spacecraft is ready to be shipped to the launch range and integrated into the launch vehicle. The duration of this phase is captured by the random variable T_{ship} that follows a lognormal distribution whose parameters were derived from historical data, as discussed in section 3.4.3.

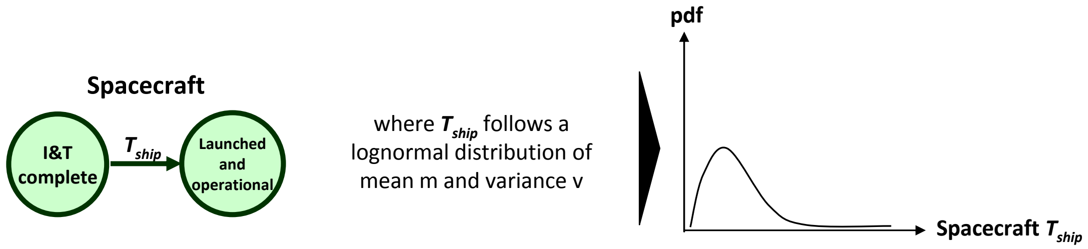


Figure 62. Model of spacecraft Integration & Testing duration (notional)

Recall the functional form of the probability density function of the random variable T_{ship} discussed in section 3.4.3:

$$f(T_{ship}, m_{ship}, v_{ship}) = \frac{1}{T_{ship}\sigma_{ship}^{2}\sqrt{2\pi}} e^{-\frac{(\ln(T_{ship})-\mu_{ship})^{2}}{2\sigma_{ship}^{2}}} \tag{6.5}$$

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

6.2.4 *Final state representation of the model of Spacecraft Time-to-Delivery*

When the three state-based models discussed previously (Instruments Development, Integration & Testing, Shipping and Launch operations) are connected to each other, a final state representation of the model of spacecraft Time-to-Delivery is obtained, as illustrated in Figure 63. Using such a state representation, this model of spacecraft Time-to-Delivery can be implemented with various stochastic tools, such as Stochastic Petri Nets (SPNs), in which the transition distributions have to be defined as presented previously. Note that the comments made in section 3.4.6 on the domain of applicability of the model of spacecraft time-to-delivery still hold, and it is still important to distinguish the conceptual contribution that the structure of the model constitutes, from the quantitative results obtained with the NASA data used in the particular application discussed in this thesis.

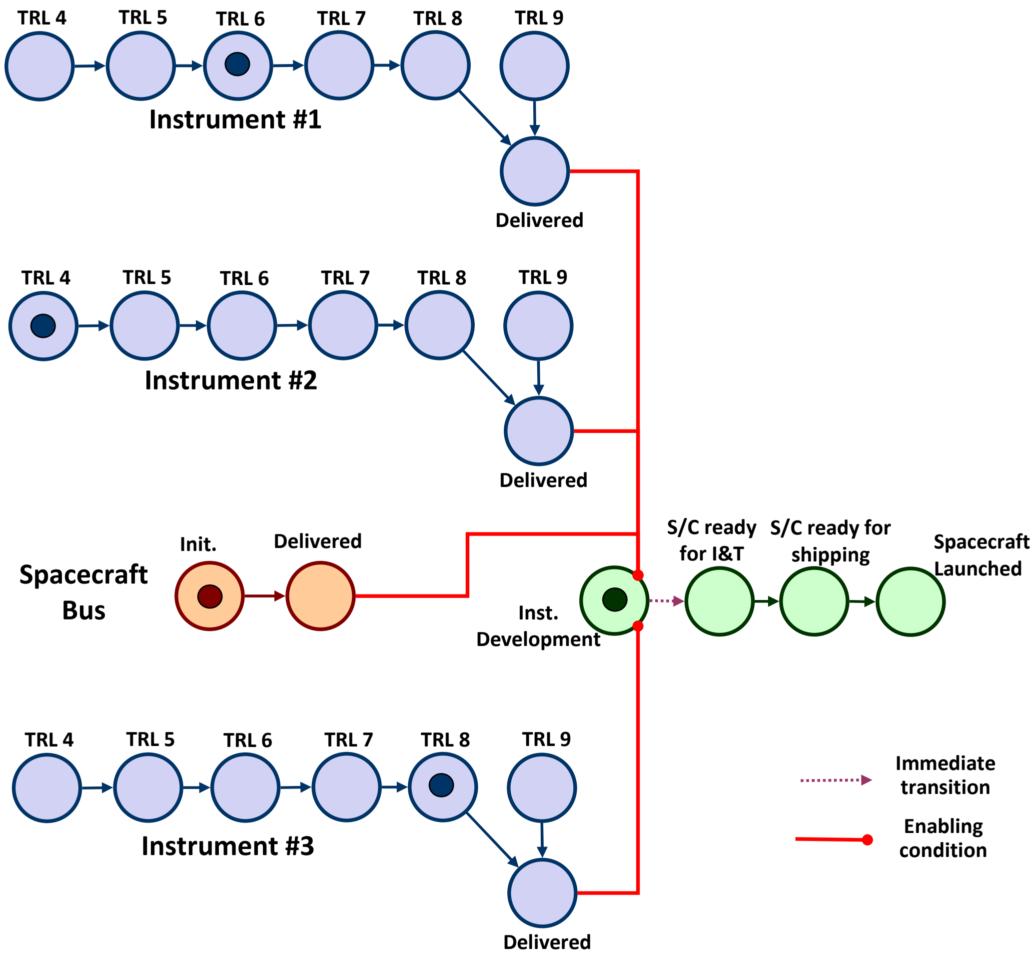


Figure 63. State representation of the model of spacecraft Time-to-Delivery, for illustrative purposes only.

For maximum flexibility, the analyses conducted in the rest of this chapter result from a manual implementation of the models in MATLAB. In the example of Figure 63, a spacecraft portfolio of $n_{inst} = 3$ instruments is considered with the following TRL configuration: **Pf = [6 4 8]**. When the instruments and the bus have reached the "delivered" state, the entire spacecraft can transition to the next stages of the development (I&T and shipping) until it is finally launched and operational on-orbit.

6.2.5 Comparative examples

In the following, the predicted schedules for three NASA missions currently proposed as a response to the Astro 2010 Decadal Survey are considered. The team responsible for each mission submitted a Response to the Request For Information (RFI) that included (at least) a master schedule with a predicted launch date, along with a technical description of the proposed spacecraft design that presented the various payload instruments and their current TRL.

Recall that for the purpose of this analysis, an “instrument” means an independent value-delivering subsystem. This definition requires that:

a. the subsystem function is not to support the general operations of the spacecraft (e.g, gyroscope, solar array) but to deliver value that is aligned with the objective(s) of the mission

b. the subsystem has to be capable to deliver value on its own, without the joint use of another subsystem

6.2.5.1 THESIS

The Terrestrial and Habitable-zone Exoplanet Spectroscopy Infrared Spacecraft (THESIS) is a mission designed around the use of a 1.4m telescope used in conjunction with molecular spectroscopy to investigate the composition and chemistry of exoplanet atmospheres [197]. The RFI response document states that “All components of THESIS […] have TRL of 6 or higher” and the predicted time-to-delivery of the system {telescope + spectrometers} is 4.5 years.

For a spacecraft portfolio **Pf = [6]**, the model of spacecraft time-to-delivery yields a Mean-Time-to-Delivery of 48 months = 4 years.

6.2.5.2 Xenia

Xenia is a mission aiming at improving our understanding of the formation and evolution of cosmic objects such as stars and galaxies. It will "use x-ray monitoring and wide-field x-ray imaging and high-resolution spectroscopy to collect essential information from three major tracers of these cosmic structures: the warm-hot intergalactic medium (WHIM), galaxy clusters, and [Gamma Ray Bursts]" [198]. The design of the spacecraft is characterized by three main independent instruments:

- The CRyogenic Imaging Spectrometer (CRIS); average TRL ~4-5
- The Transient Event Detector (TED); average TRL ~ 6
- The High Angular Resolution Imager (HARI); average TRL ~ 6

According to the RFI response documentation, the predicted time-to-delivery is approximately 7 years [199].

For a spacecraft portfolio **Pf = [5 5 6]** the model of spacecraft time-to-delivery yields a Mean-Time-to-Delivery of 83 months = 6.9 years.

6.2.5.3 International X-Ray Observatory (IXO)

The International X-Ray Observatory (IXO) is a mission that proposes to address astrophysical questions that for example relate to the evolution of black holes [200].

The design of the spacecraft is characterized by five main independent instruments:

- The X-Ray Microcalorimeter Spectrometer (XMS); TRL ~ 4
- The Wide Field and Hard X-Ray Imager (WFI/HXI); TRL ~ 4
- The X-Ray Grating Spectrometer (XGS); TRL < 4
- The X-Ray Polarimeter (XPOL); TRL ~ 5

- The High Time Resolution Spectrometer (HTRS); TRL ~ 6

According to the RFI response documentation, the predicted time-to-delivery is approximately 12.5 years [200].

For a spacecraft portfolio **Pf = [4 4 4 5 6]** the model of spacecraft time-to-delivery yields a Mean-Time-to-Delivery of 138 months = 11.5 years. (Note that the model does not consider technologies that are still at the formulation stage, i.e., TRL ≤ 3, and that the value of TRL 4 was used for the XGS while the reference documents a lower level of maturity for that instrument, which may explain partially the shorter MTTD obtained by the model).

These results should be treated with caution. The purpose of these comparisons is not to convince of the accuracy of the model; these examples merely provide some assurance that the Mean-Time-to-Delivery produced by the model lies within a “reasonable” range of values and that it is consistent with estimates from some NASA missions currently proposed.

6.3 Operations module: instrument-centric model of obsolescence

The stochastic model of spacecraft obsolescence presented in Chapter 4 was system-centric: each state of the Markov chain represented the level of obsolescence of the entire spacecraft. While this approach provided general trends highlighting the influence of selected design parameters on the risk of obsolescence, a higher level of fidelity in the definition of the states is required to understand what drives the obsolescence of the spacecraft. Specifically, since each instrument or spacecraft subsystem serves a specific function, it can be reasonably argued that each one can be rendered obsolete independently from the others. This section therefore proposes to extend and refine the analysis of on-orbit obsolescence conducted in Chapter 4 by modeling the obsolescence phenomenon at the instrument (or subsystem) level. This approach is aligned with the spacecraft portfolio concept formulated in Chapter 3 and presents benefits:

- It offers an opportunity to identify instruments/subsystems that go obsolete the fastest, and to isolate them from others that are less prone to obsolescence.

- When obsolescence data is available, it allows the infusion of this data more easily in the models by targeting the relevant subsystems, as opposed to the "entire spacecraft".

6.3.1 Instrument obsolescence

When conceiving a spacecraft as a portfolio of instruments, TD_i is a random variable representing the time needed to fully develop an instrument and have it ready for integration in the whole spacecraft. The concurrent development of all the instruments constituting the spacecraft portfolio has consequences on the final delivery schedule of the entire spacecraft, described by another random variable $TD_{s/c}$. Similarly, in a subsystem-level approach of obsolescence, the time elapsed until the onset of obsolescence of a given instrument is captured by a random variable.

Figure 64 shows a state representation of the model of obsolescence for a given instrument of the portfolio. Similarly to the system-level model presented in section 5.7.1, three main states are used to describe a given instrument *i* of the portfolio: State-of-the-Art (SoA_i), minor Obsolescence (mO_i) and Major Obsolescence (MO_i). As discussed in section 5.7.1, it is assumed that no on-orbit servicing is performed, precluding any return from an obsolete state (minor obsolete or major obsolete) to the State-of-the-Art state.

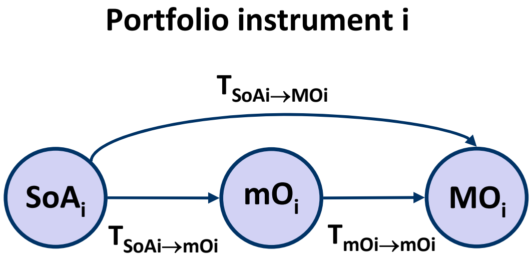


Figure 64. State representation of the obsolescence model for each portfolio instrument.

The proper formulation of such models at the instrument/technology level requires:

- an understanding of the manifestation of obsolescence for the instrument considered, and the resulting definition of the states SoA_i, mO_i and MO_i, based on performance levels for example.
- the selection of the transition probabilities from one state to the next.

In his survey of sensors used for Earth observation mission, Kramer [201] provides relevant data that can serve as a basis to derive data-driven obsolescence transition laws. The next three subsections present examples of the use of obsolescence data (for a given class of instruments/technologies) to define the transition probabilities between the various obsolescence states.

6.3.2 Calibration of transition probabilities using data: examples

6.3.2.1 Obsolescence of land surface imaging instruments

Adapted from Kramer [201], Figure 65 shows the evolution of the spatial resolution of the sensors used on surface imaging missions from 1970 to 2010.

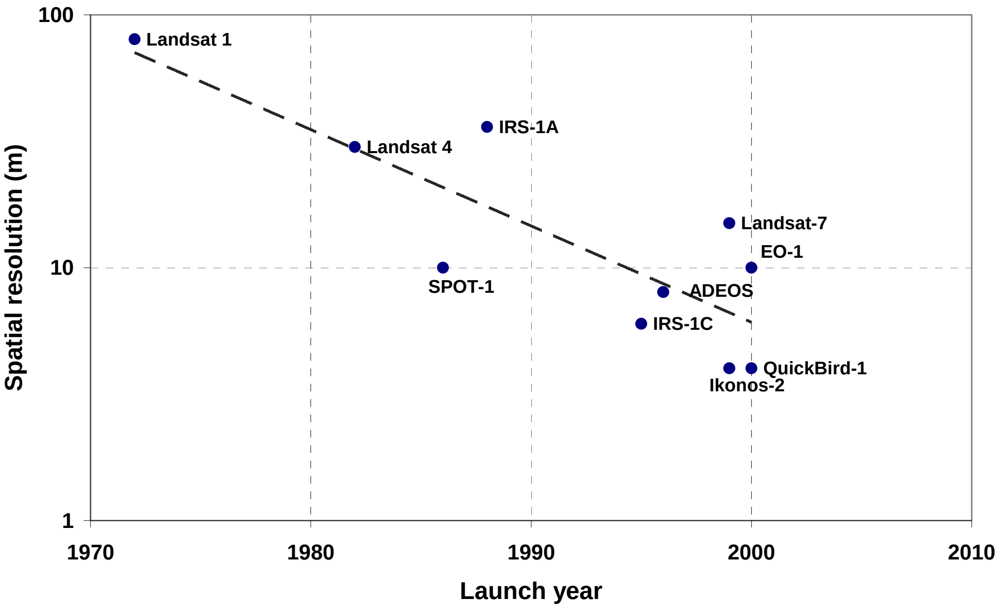


Figure 65. Spatial resolution of surface imaging sensors since 1970. Adapted from Kramer [201].

Visual inspection of Figure 64 confirms the expected improvement in spatial resolution of the sensors used for surface imaging missions over time. This general trend can be captured from Figure 64 by performing a linear regression analysis on the data points, resulting in the formulation of a simple functional form for the spatial resolution as a function of time. For example, if the variable *t* represents the number of years since 1970, the following function can be assumed:

$$Rs = \alpha_{Rs}\, e^{-\beta_{Rs} t} \tag{6.6}$$

with $\alpha_{Rs} = 83.4871$ and $\beta_{Rs} = 0.0877$

Using the previous law, an estimate of the time required for the spatial resolution to be divided by a given factor *r* can be calculated as follows:

$$\Delta T_r = \frac{\ln r}{\beta_{Rs}} \tag{6.7}$$

- If the major obsolescence state is defined by the emergence of a competing sensor technology that allows to gain a factor 10 in the spatial resolution, the Mean-Time-To-Major-Obsolescence is:

$$MTT(SoA \rightarrow MO) = \frac{\ln 10}{\beta_{Rs}} \approx 26.3\, years \tag{6.8}$$

- If the minor obsolescence state is defined by the emergence of a competing sensor technology that allows to gain a factor 2 in the spatial resolution, the Mean-Time-To-minor-Obsolescence is:

$$MTT(SoA \rightarrow mO) = \frac{\ln 2}{\beta_{Rs}} \approx 7.9\, years \tag{6.9}$$

These Mean-Times-To-Obsolescence are used as the central parameter in the probability distribution governing the transition from one state to another. In the light of the obsolescence modeling schemes discussed in Chapter 4, let us assume that the time to transition to the Major Obsolete state $T_{SoA \rightarrow MO}$ follows a negative exponential distribution:

$$f(T_{SoA \rightarrow MO}) = \lambda_{MO} e^{-\lambda_{MO} t} \tag{6.10}$$

In Eq. 6.10, the random variable $T_{SoA \rightarrow MO}$ has an expected value that is equal to the parameter λ_{MO}. As a result, the parameter λ_{MO} can be defined as from the previous analysis by setting $\lambda_{MO} = MTT(SoA \rightarrow MO) \approx 26.2$ years.

6.3.2.2 Radar altimeters

Similarly, Kramer [201] provides range precision data concerning radar altimeters that have been flown on space missions since 1970. A similar approach can be used to define the obsolescence states of radar altimeters as well as Mean-Times-to-Obsolescence.

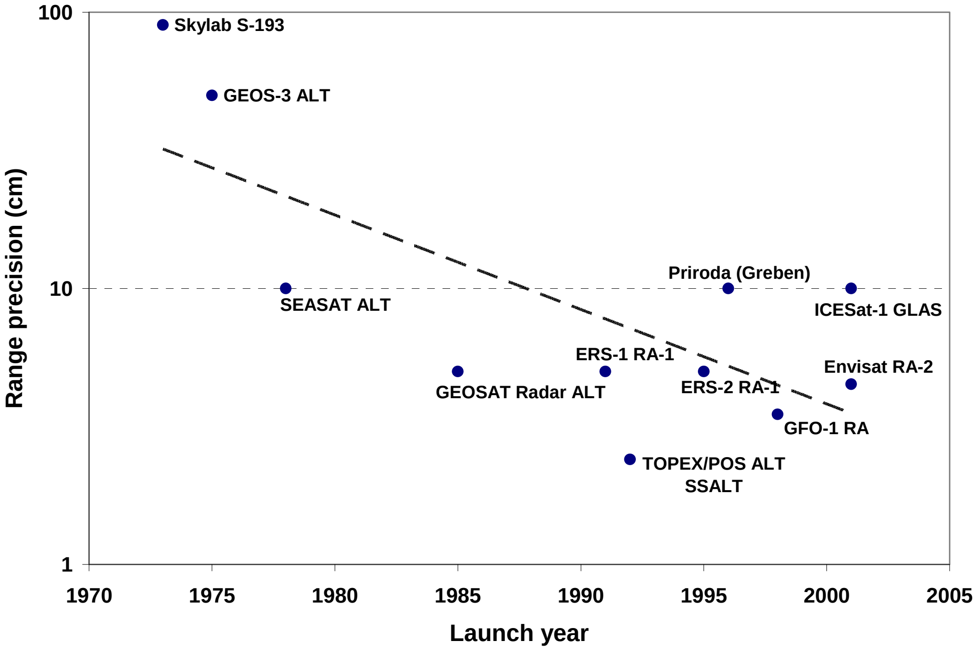


Figure 66. Range precision of radar altimeters sensors since 1970. Adapted from Kramer [201].

6.3.2.3 SAR instruments

Kramer [201] also provides the spatial resolution of Synthetic Aperture Radars (SAR) that have been flown on space missions since 1975. A similar approach can be used to define the obsolescence states of Synthetic Aperture Radars as well as Mean-Times-to-Obsolescence.

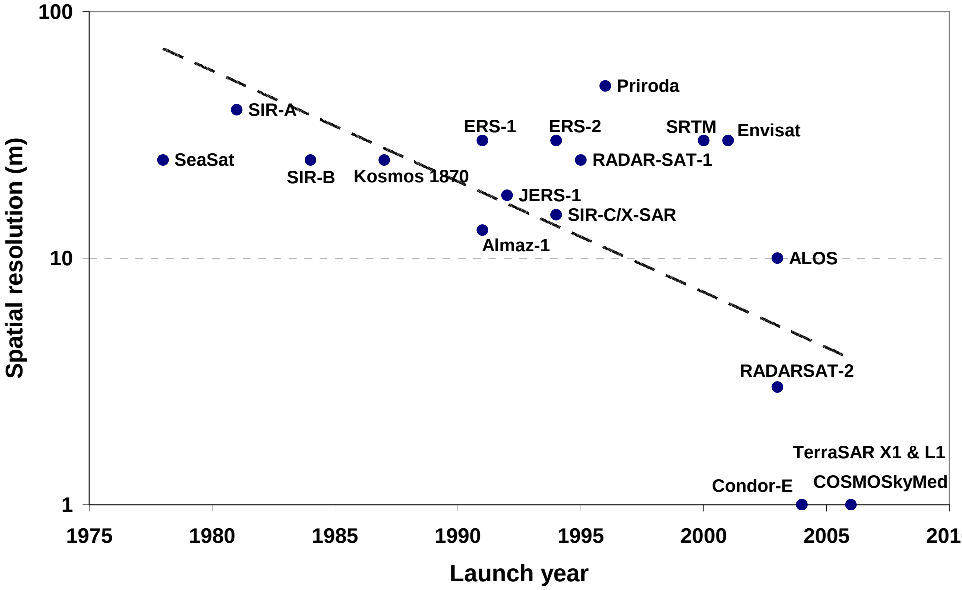


Figure 67. Spatial resolution of Synthetic Aperture Radars since 1975. Adapted from Kramer [201].

Note that one performance metric (e.g., spatial resolution or range precision) may not be sufficient to fully reflect the quality of the service provided by the instruments considered. Further analyses along other dimensions of performance (e.g., data rate) may help to define more appropriately the states of obsolescence.

6.4 Operations module: failure model and replacements

6.4.1 Failure model

The service delivered by a spacecraft may end prematurely if the spacecraft experiences a failure resulting in the total loss of functionality of one or several of its payload instruments.

The operations module is designed to capture this eventuality through the use of two main states (Operation or Failed) representing the functionality status of each portfolio instrument, as illustrated in Figure 68.

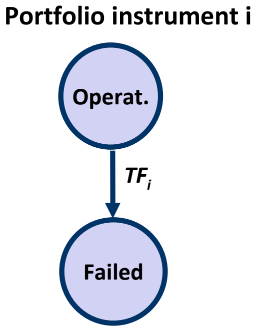


Figure 68. State representation of the functionality status of each portfolio instrument

For each instrument *i*, the Time-to-Failure since spacecraft launch TF_i is treated as a random variable, and its probability density function can be derived from historical reliability data. For the purpose of this study, the single Weibull model of spacecraft reliability developed by Castet and Saleh [202] was selected.

6.4.2 Replacement strategy

The integrated framework allows simulating the development and launch of a series of spacecraft responding to a given need. In that simulation mode, it is assumed that within a given series of spacecraft, each spacecraft will be designed based on the same technology portfolio configuration than its predecessor (same number of instruments and TRL configuration) and the same design lifetime T_{life}.

6.4.2.1 Date of development start for subsequent spacecraft

In order to minimize the likelihood of service discontinuation and to help guarantee that a new spacecraft will be ready as soon as its predecessor reaches its design lifetime, the decision to start the development of a subsequent spacecraft is made according to the same strategy that was discussed in Chapter 5. Specifically, for the subsequent spacecraft, this decision is based on an estimate of the time-to-delivery of that subsequent spacecraft as well as the common design lifetime T_{life} that characterize all the spacecraft of the series. In the model, the projected time-to-delivery of the next spacecraft is equal to the time-to-delivery of the previous spacecraft. The calendar time t_k* of the development start (e.g., date of the Authority-To-Proceed) of the k^{th} spacecraft of a series is calculated as follows:

$$\begin{array}{ll} \text{For } k = 1 & t_k^* = 0 \\ \text{For } k > 1 & t_k^* = t_{k-1}^* + TD_{s/c(k-1)} + \max\left[0, T_{life} - TD_{s/c(k-1)}\right] \end{array} \tag{6.11}$$

This criterion ensures that:

- The development of a new spacecraft will not start until the previous spacecraft is launched
- The development of a new spacecraft starts *before* the previous spacecraft reaches its design lifetime; specifically it is scheduled to have the spacecraft ready for launch when the previous one reaches its design lifetime.

6.4.2.2 Launch date of subsequent spacecraft

An additional condition is implemented that specifies that if the next spacecraft is ready for launch before the previous spacecraft has completed its mission, it remains on stand-by and is only launched once the previous spacecraft has reached its design lifetime.

6.5 An integrated framework for the modeling of spacecraft schedule and on-orbit obsolescence

This section describes how the various models described previously are now connected to each other to form an integrated framework that allows for the calculation of spacecraft time-to-delivery, risk of on-orbit obsolescence and the evaluation of the utility delivered by a given spacecraft portfolio configuration.

6.5.1 State representation

Figure 69 is a state representation of the integrated framework showing both the development module (with the model of spacecraft Time-to-Delivery) and the operations module (including the obsolescence and failure models).

Several model characteristics that are visible on Figure 69 should be noted:

- For a given instrument *i*, the model of time-to-delivery and the obsolescence model are connected. It is assumed that the "obsolescence clock" of instrument *i* starts ticking only once this instrument/technology is delivered. In other words, the delivery of a given instrument/technology is an enabling condition for the start of the obsolescence process of said instrument (represented by a red link in Figure 69). This assumption is made to ensure that a technology that is still going through the maturation process is not already subject to obsolescence. (Without this assumption, a technology starting at TRL 4, thus more innovating, would take longer to be delivered and would then be subject to a higher risk of obsolescence than an already proven (TRL 9) technology, producing a counterintuitive trend).

- The "failure clock" for each instrument is triggered when the spacecraft is launched.
- When the spacecraft or instrument *i* experiences a total failure, instrument *i*, regardless of its obsolescence state, immediately transitions to the "Failed" state. In other words, an instrument or spacecraft total failure is an enabling condition for the immediate transition to the failed state.

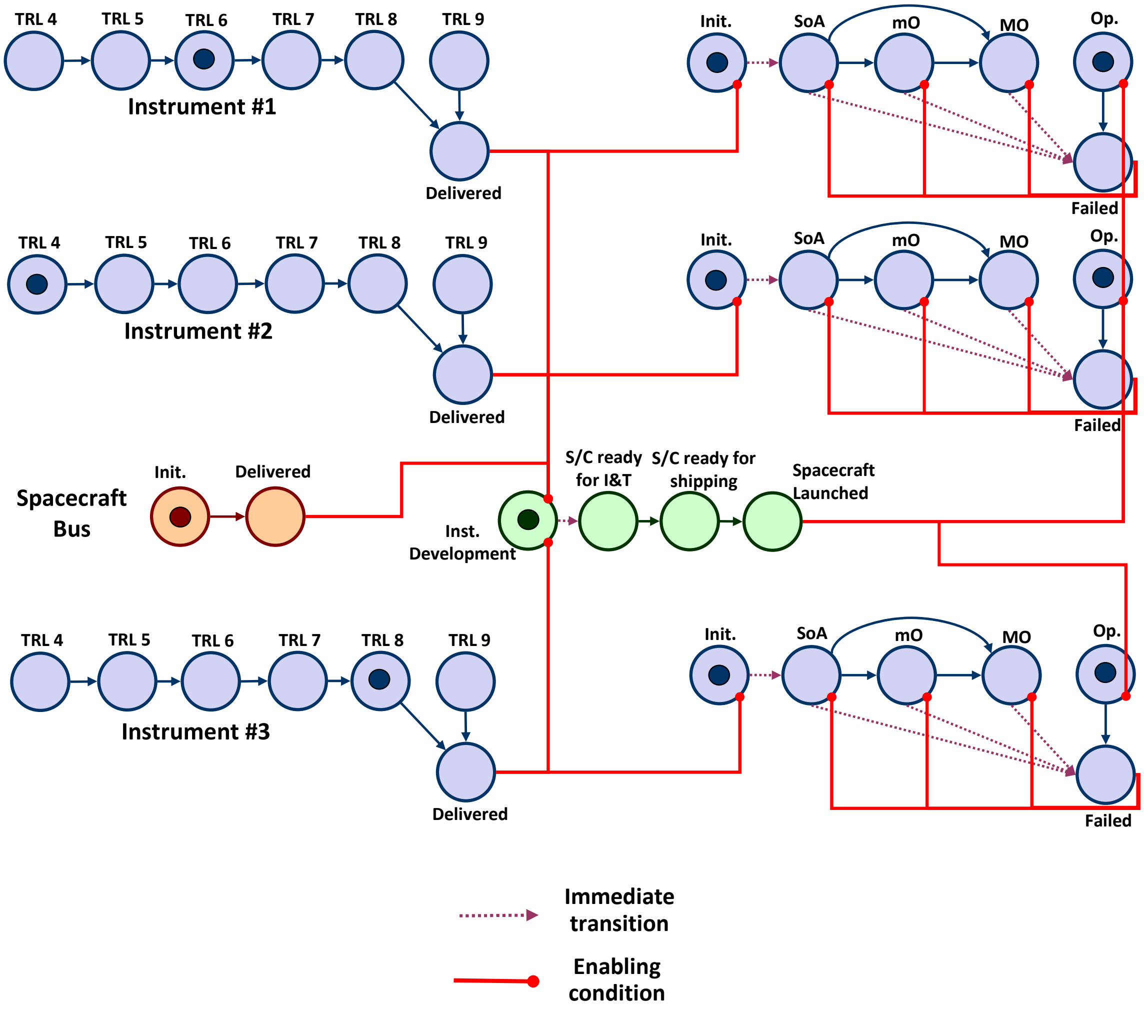


Figure 69. State representation of the complete integrated framework for a spacecraft portfolio of $n_{inst} = 3$ instruments (illustrative)

The spacecraft can only deliver utility if it has been launched **and** some of its instruments are operational. The extent to which the operational instruments are obsolete determine how much instantaneous utility is delivered. The following two subsections discuss the specific assumptions that govern the calculation of the utility delivered by each instrument.

6.5.2 Refinements to the use of the spacecraft utility

Chapter 3 introduced the notion of utility, defined as a scalar representing the satisfaction derived from the services provided by the system to the customer per unit time. The analyses presented in Chapter 3 were conducted by making two important assumptions:

1. Each portfolio instrument delivers the same instantaneous utility (that was set to 1)
2. The instantaneous utility delivered by the instruments is constant throughout the life of the spacecraft

Those assumptions are now lifted and the next sections discuss how to scale the instantaneous instrument utilities in a manner that should capture not only the performance benefits offered by innovative (low-TRL) instruments but also the impact of obsolescence on the service delivered.

6.5.2.1 Capturing the value of innovation

Recall that Eq. 27 from Chapter 3, shows the instantaneous instrument utilities as a vector:

$$\hat{\mathbf{u}}_{s/c} = \left[\hat{u}_1 \quad \hat{u}_2 \quad \ldots \quad \hat{u}_n\right] \tag{6.12}$$

The analyses conducted in Chapter 3 assumed that for every instrument i, $\hat{u}_i = \hat{u}_0 = 1$, regardless of the initial TRL of instrument i. In reality, the development of new technologies is undertaken in order to yield some benefits. For example, a technology that is currently at TRL 4 is typically being developed because it is expected to provide some improvements in terms of performance, reliability, cost, etc. compared to existing technologies that are at TRL 9. If trade studies that compare the various cumulative utilities delivered by different design options (i.e., spacecraft portfolio configurations) are to be conducted, this "value of innovation" should be captured by the instantaneous utilities.

In the remainder of this work, the instantaneous instrument utilities $\hat{u}_i$ are thus varied based on the different values of the instrument TRLs. **It is contended that $\hat{\mathbf{u}}_i$ should be a decreasing function of the initial instrument TRL.** For example, for a portfolio of four instruments

Pf = [4 4 7 9], one could define the vector of instantaneous instrument utilities as: $\hat{\mathbf{u}}_{\mathbf{s/c}}$ = **[3 3 2 1]**, if the two instruments at TRL 4 are considered to offer "three times as much" utility as a similar instrument that has been flown on previous space missions (TRL 9). (Consider for example an existing radiometer at TRL 9 with a data rate of several Mbps vs. a future radiometer currently at TRL 4, with similar specifications, but offering a larger data rate of several tens of Mbps.)

6.5.2.2 Impact of obsolescence on utility

The stochastic framework developed in Chapter 5 provides quantitative results regarding the likelihood of system obsolescence, and relates it to selected design parameters, namely the design lifetime T_{life} and the initial system-TRL level TRL_{ini}. In portfolio theory, as implemented in the field of Research & Development, projects (or products) that are providing a diminishing return on investment, therefore no longer supporting the company's strategic objectives (and that can thus be considered "obsolete") are allocated fewer resources, deprioritized or terminated.

In a similar fashion, this section proposes to model the impact of instrument obsolescence on the service provided to the customer through a reduction of the utility delivered. Depending on the state of obsolescence of the instrument *i*, its instantaneous utility delivered is scaled down from its initial value when the technology was state-of-the-art. This is formalized in the following manner:

$$\hat{u}_{tot}(t) = \sum_{i=1}^{n} c_i \hat{u}_i \tag{6.13}$$

where the coefficient c_i depends on the current obsolescence state of instrument *i*, that is:

$c_i = c_{SoAi}$ if instrument *i* is at the state "State-of-the-Art"

$c_i = c_{mOi}$ if instrument *i* is at the state "minor Obsolescence"

$c_i = c_{MOi}$ if instrument *i* is at the state "Major Obsolescence"

By default, $c_{SoAi} = 1$ was selected. Examples of values used in the following analyses include:

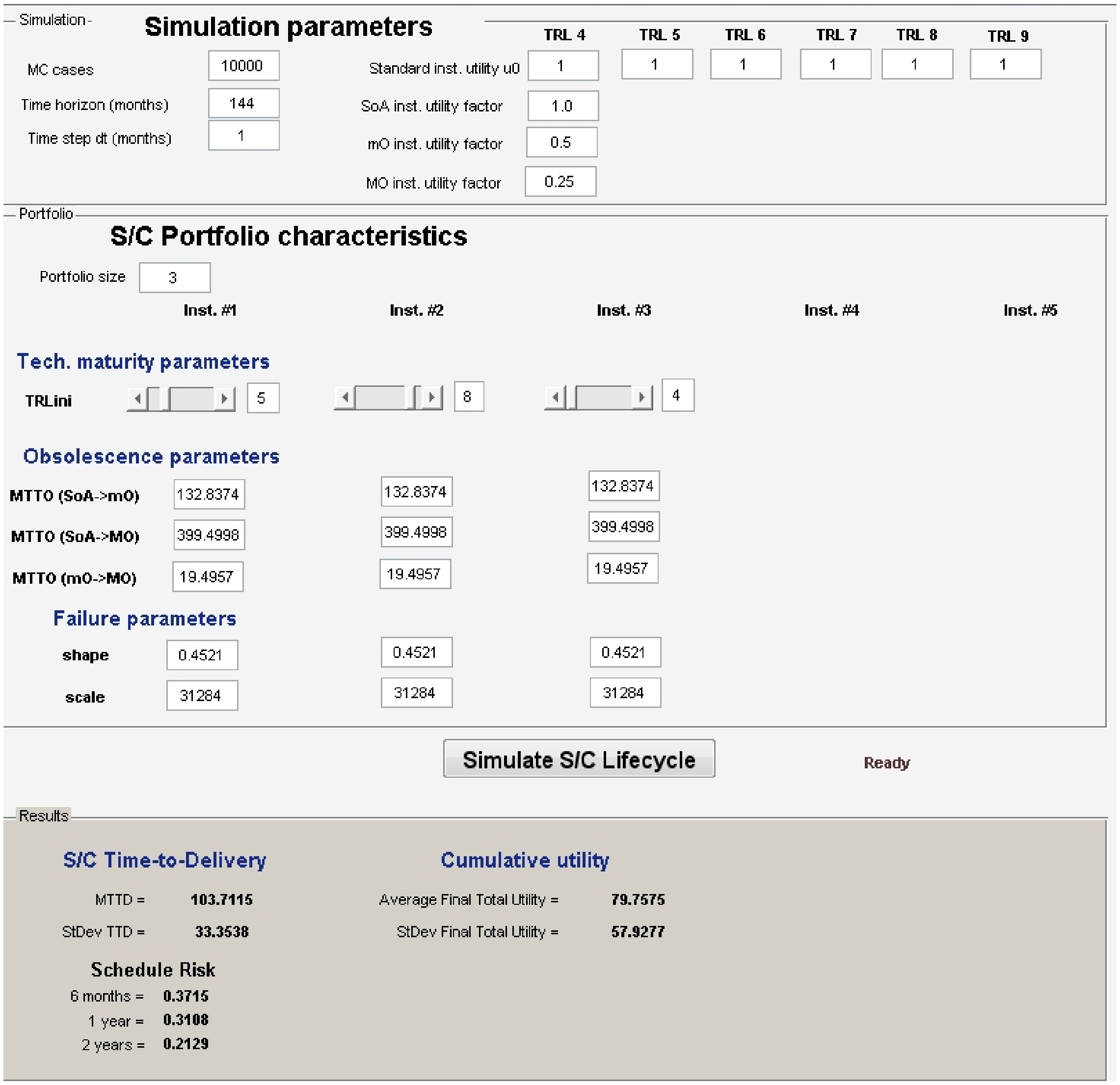
$c_{mOi} = 0.5$ and $c_{MOi} = 0.25$.

6.5.3 Simulation tool with Graphical User Interface (GUI)

In order to conduct the design space exploration and investigate the implications of spacecraft portfolio choices on schedule and cumulative utility, the models are controlled by a simulation tool with a Graphical User Interface (GUI). As shown in Figure 70, this

GUI can take as inputs various model parameters: number of Monte-Carlo cases, time horizon τ_{ops}, portfolio characteristics including number of instrument n_{inst} and various instrument TRLs, instantaneous instrument utilities $\hat{u}_i$ based on their TRL, c_i obsolescence coefficients, and finally obsolescence and failure parameters of the probability distributions describing the transition times for each instrument. For a given portfolio configuration, the results returned by the GUI include Mean-Time-to-Delivery as well as various levels of schedule risk, and average and standard deviation of the total cumulative utility at the end of the time horizon. In addition, plots of the distribution of the random variable spacecraft time-to-delivery $TD_{s/c}$ and utility profiles (that are presented next) are produced.

Varying the portfolio characteristics via for example the instrument TRL "knobs" allows the dynamic exploration of the design space as the output metrics and plots are updated in real-time. The specific impact of a change in portfolio size or instrument TRLs can thus be immediately visualized.



MC cases 10000

Time horizon (months) 144

Time step dt (months) 1

	TRL 4	TRL 5	TRL 6	TRL 7	TRL 8	TRL 9
Standard inst. utility u0	1	1	1	1	1	1

SoA inst. utility factor 1.0

mO inst. utility factor 0.5

MO inst. utility factor 0.25

Portfolio size 3

	Inst. #1	Inst. #2	Inst. #3	Inst. #4	Inst. #5
Tech. maturity parameters					
TRLini	5	8	4		
Obsolescence parameters					
MTTO (SoA->mO)	132.8374	132.8374	132.8374		
MTTO (SoA->MO)	399.4998	399.4998	399.4998		
MTTO (mO->MO)	19.4957	19.4957	19.4957		
Failure parameters					
shape	0.4521	0.4521	0.4521		
scale	31284	31284	31284		

S/C Time-to-Delivery

MTTD = 103.7115

StDev TTD = 33.3538

Cumulative utility

Average Final Total Utility = 79.7575

StDev Final Total Utility = 57.9277

Schedule Risk

6 months = 0.3715

1 year = 0.3108

2 years = 0.2129

Figure 70. Graphical User Interface (GUI) of the simulation tool

6.5.4 Further directions to validate the integrated framework

Further steps to validate the integrated framework would include:

- Collecting a larger sample of spacecraft with data regarding the initial instruments TRL at the program start, the total number of instruments, and the duration of each main schedule phase. For this larger sample, the following tests could be perform:

- probability plots on the sample to validate the use of a given distribution type for each phase. It could for example provide some justification of the **use of lognormal distributions** for the integration & testing and shipping phases (preliminary lognormal probability plots with the current data used in this thesis and their interpretation are provided in Appendix B). If these tests are unsuccessful (data points representing the various integration & testing durations not aligned on a lognormal probability plot), probability plots testing other types of distributions (e.g., Weibull, Gamma) shall be used until an appropriate family of distribution can be identified.
- Assuming that the type of distributions used by the model (e.g., lognormal in this thesis) is indeed appropriate to model the duration of those phases, more sophisticated goodness of fit tests can provide quantitative information to further validate the parameters of these distributions. These include for example the Kolmogorov-Smirnov test [203] that provides a p-value based on the maximum difference between the empirical cumulative distribution function (from the data) and the cumulative distribution function from the model. An example of this test for the duration of the shipping phase is provided in Appendix A. If the parameters of the distribution are found to be inadequate, various methods can be considered to obtain appropriate parameters, such as Least Square Fits on the probability plots, non-linear Least Square Fits on the empirical c.d.f, or Maximum Likelihood Estimation (MLE) on the data.

- Analyzing the master schedule of a larger number of spacecraft to unveil the most common structure and compare it to the three-phase structure (Instruments Development, Integration & Testing, and Shipping) proposed in this framework.

Since the obsolescence model and failure model of the operations module have parameters that are directly input by the user (depending on the type of instruments considered), their validation remains context-specific.

The following section now discusses the main results obtained with the integrated framework, by presenting utility profiles for single spacecraft as well as series of spacecraft, and then proposing two mission scenarios.

6.6 Results

6.6.1 *Utility profiles*

6.6.1.1 Instruments utilities and utility profile for a single spacecraft

Figure 71 shows an example of temporal profiles for the 3-instrument portfolio **Pf = [7 9 6**] for a time horizon of τ_{ops} = 12 years = 144 months. Note that all the events represented on this figure (transitions to delivered, obsolete or failed states) correspond to the average values of the random variables calculated via the Monte-Carlo simulations.

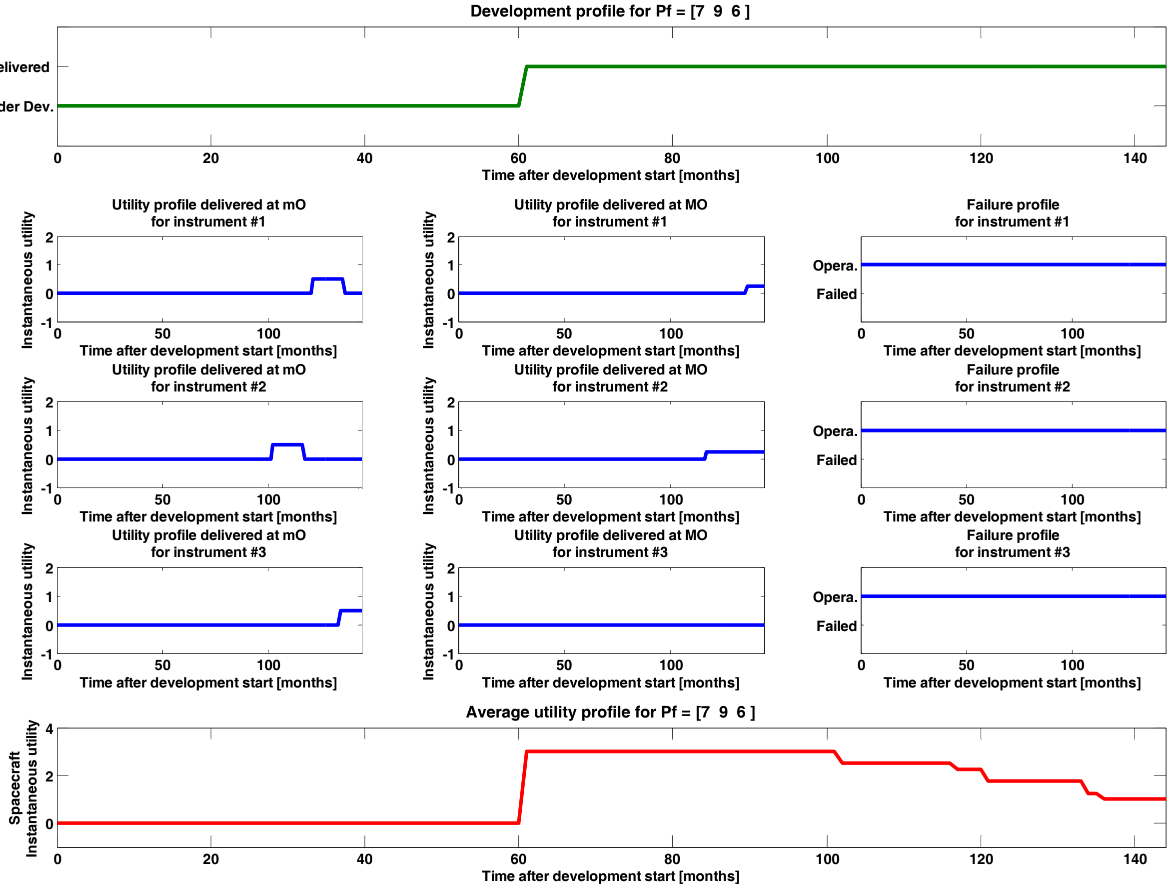


Figure 71. Examples of utility profiles for a 3-instrument portfolio

- The top plot represents the development and then operations of the corresponding spacecraft. The Mean-Time-to-Delivery for this spacecraft portfolio was found to be 61 months, as illustrated by the jump from “Under Development” to “Delivered” at t = 61 months.
- Among the 9 central subplots, each row is associated with one particular instrument (e.g., row 1 corresponds to the 1st instrument that is at $TRL_{ini} = 7$). Each row of plots provides three utility profiles, based on whether the instrument has transitioned to the “minor Obsolescence” state, “Major Obsolescence” state or “Failed” state. For example, on row 2, instrument 2 becomes “minor obsolete” at t

= 102 months, after which it only delivers a fraction of the initial utility, i.e., $c_1\,\hat{u}_1$ = 0.5 units of utility (far-left plot). At t = 117 months, instrument 2 becomes "Major Obsolete", after which it only delivers $c_1\,\hat{u}_1$ = 0.25 units of utility (middle plot). The far-right plot of row 2 shows that instrument 2 has remained operational until t = τ_{ops}.

- The bottom plot represents a combination of all the plots above and shows the average utility profile for the spacecraft portfolio **Pf = [7 9 6]**. The spacecraft MTTD is still visible at t = 61 months (no utility is delivered before that date), and the total instantaneous utility delivered by the spacecraft is the sum of the instruments instantaneous utilities. For example, three units of utility are delivered by the spacecraft until t = 102 months, date at which instrument #2 is the first instrument to become obsolete. The full spacecraft utility profile reflects both the significance of the time-to-delivery as well as the impact of obsolescence on the total utility delivered over time until the time horizon is reached.

Note that since instrument #2 is the most technologically mature (TRL_{ini} = 9), it is the one that becomes obsolete the earliest. Also, the consecutive transitions to obsolescence of the various spacecraft instruments result in a significantly reduced utility delivered at the end of the time window: $\hat{u}_{tot}(t=144)$ = 1 unit of utility < $\hat{u}_{tot}(t=MTTD)$ = 3 units.

6.6.1.2 Utility profile for a series of spacecraft (replacement strategy)

Figure 72 represents the temporal profiles of the cumulative utility delivered by a series of spacecraft based on the portfolio **Pf = [7 7]**, and with T_{life} = 4 years, developed consecutively to maintain a certain service. Note that this figure only represents one specific Monte-Carlo run.

The top plot shows the overall utility delivered over time, through the replacement of the consecutive spacecraft. During, the first 80 months, utility is delivered via the 1st spacecraft that is launched at $t = 32$ months, as seen on the 2nd plot.

Based on Eq. 6.11, the calendar date of the development start of the 2nd spacecraft (or ATP of spacecraft #2) is $t_2^* = 0 + 32 + \max(0, 4*12 - 32) = 48$ months. Assuming that the time-to-delivery of the 2nd spacecraft will be similar to the time-to-delivery of the 1st spacecraft (i.e., 32 months), the development of the 2nd spacecraft starts at $t_2^* = 48$ months, so that it is ready when the 1st spacecraft reaches its design lifetime and is retired. The 3rd plot shows that spacecraft #2 is actually delivered $TD_{s/c\ 2} = 45$ months after the development start or ATP date. As a result, the top plot shows that service is discontinued (no utility is provided) between the retirement of spacecraft #1 ($t = 80$ months) and the launch of spacecraft #2 (occurring at $t = t_2^* + TD_{s/c\ 2} = 48 + 45 = 93$ months). In a similar fashion, the development start of the 3rd spacecraft is scheduled for $t_3^* = t_2^* + TD_{s/c\ 2} + \max(0, T_{life} - TD_{s/c\ 2}) = 48 + 45 + (48 - 45) = 96$ months in calendar time. The time-to-delivery of the 3rd spacecraft $TD_{s/c\ 3} = 30$ months is actually shorter than that of the 2nd spacecraft. Instead of being launched when it is ready, (that is, at $t = t_3^* + TD_{s/c\ 3} = 96 + 30 = 126$ months), the 3rd spacecraft remains on stand-by until the end of the mission of the 2nd spacecraft, occurring at $t = 93 + 4*12 = 141$ months, ensuring no discontinuation of service.

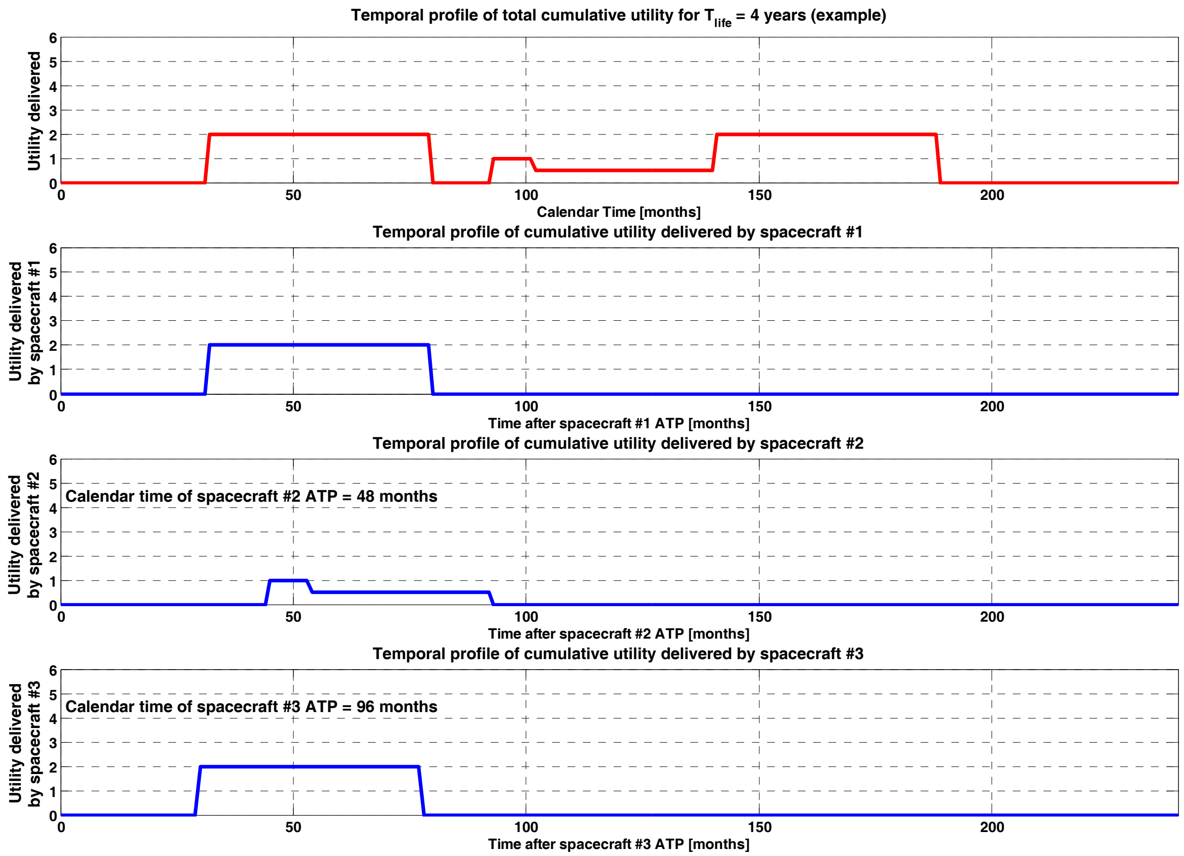


Figure 72. Examples of utility profiles for a series of spacecraft of T_{life} = 4 years and τ_{ops} = 20 years

The choice of the spacecraft portfolio configuration (number of instruments and TRLs) as well as the design lifetime of the spacecraft will impact the delivery-retirement dynamics, modifying the shape of the total utility profile (top plot of Figure 72). In other words, the design decisions leading to the selection of a given spacecraft portfolio have important implications on the total utility delivered over the time horizon of interest.

6.6.2 Calendar Risk of On-Orbit Obsolescence and Schedule Risk

The concept of calendar risk of on-orbit obsolescence was introduced in Chapter 5 at the system-level. In a similar fashion, the calendar risk of on-orbit obsolescence for an instrument i CRO$_i$ can be defined as the probability that the instrument will be obsolete at a given date t in the future, provided that the spacecraft is on orbit:

$$CRO_i(t) = \Pr\{obsolete_i | on-orbit\}(t) = \frac{\Pr\{obsolete_i \ AND \ on-orbit\}(t)}{\Pr\{on-orbit\}(t)} \tag{6.14}$$

The integrated framework now allows the simultaneous investigation of the impact of TRL on the instrument calendar risk of on-orbit obsolescence and on spacecraft schedule risk. By analogy to Figure 57, Figure 73 shows an example of a calendar obsolescence – schedule risk plot for an instrument in a 2-instrument spacecraft portfolio. For each value of the initial TRL used for instrument #1 at the start of the development of the spacecraft, Figure 73 provides the resulting calendar risk of on-orbit obsolescence (CRO) of that instrument at t = 5 years after the development start, as well as the schedule risk at 5 years (i.e., the risk that the spacecraft time-to-delivery will exceed 5 years).

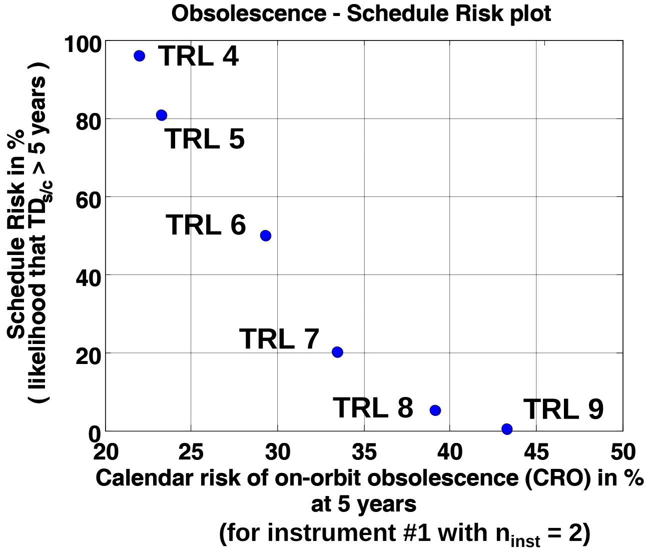


Figure 73. Calendar obsolescence – Schedule risk plot

In agreement with the discussion conducted in section 5.7.5, Figure 73 shows a case in which the CRO at t = 5 years increases when the initial TRL of instrument #1 increases. Specifically, the instrument CRO increases from 22% when TRL$_{ini}$ = 4 to 43% when

TRL_{ini} = 9. This provides some validity to the rationale used by the DOD to continue developing technologies with low maturity in order to reduce the calendar risk of on-orbit obsolescence.

More importantly, the figure also confirms that the likelihood of the spacecraft not to be delivered within 5 years increases dramatically when the initial TRL of instrument #1 decreases (from 0% when TRL_{ini} = 9 to 96% when TRL_{ini} = 4), in agreement with the findings of Chapter 3Figure 3. As a result, there exists in that case a trade-off between schedule risk and calendar risk of on-orbit obsolescence, that Figure 73 allows highlighting. In other words, using low maturity technologies ($TRL_{ini} \leq 8$) at the start of the development of a spacecraft can result in a reduction of the instrument calendar risk of on-orbit obsolescence in the short-term, but this comes at a price of a higher chance of the spacecraft not to be delivered for that date.

Recall that the purpose of the framework developed herein is to contribute to inform design decisions that are meant to meet the mission requirements. The next section thus proposes to consider two main mission scenarios (science mission and defense mission), with specific sets of requirements, and shows, in each case, how the new framework help unveil the appropriate design decisions and trade offs.

6.6.3 Scenarios and examples of application

6.6.3.1 Science mission scenario

In this scenario, the case of a single science mission (with no follow-on) that is schedule-risk driven, and for which a high science return desired, is analyzed. Consider for example an interplanetary mission to Mars with a design lifetime of T_{life} = 2 years. In that case, science starts being collected only once the destination (Mars vicinity) has been reached. Due to the 26-month synodic period of the system Earth-Mars, launch opportunities only occur at determined dates. Besides the objective of meeting a given launch window, there is no special incentive or utility benefit in launching earlier. The design space exploration is therefore conducted in a clock-based mindset.

Main requirement: the spacecraft must be ready within the next 8 years, i.e., $TD_{s/c} \leq 96$ months (which corresponds to the date of the targeted launch window). The acceptable level of schedule risk (i.e., the likelihood that the spacecraft will *not* be ready within 96 months), is set to the value of 5 %.

Design decisions: how many instruments (n_{inst}) and what level(s) of technology maturity (TRLs) should be selected in order to remain under the level of schedule risk agreed upon and to ensure high science return?

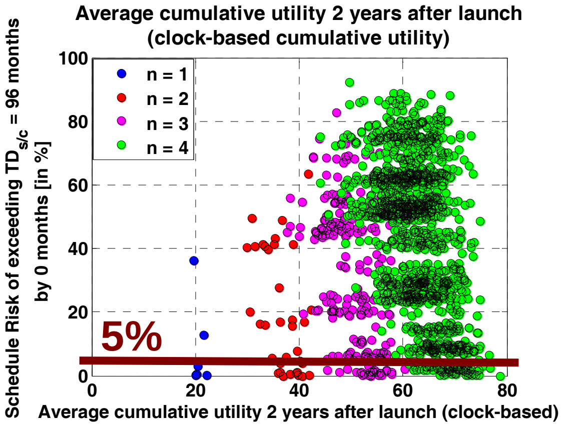


Figure 74. Schedule risk of exceeding 96 months and average cumulative utility after T_{life}= 2 years for spacecraft portfolios of size ranging from 1 to 4 instruments

For all the spacecraft portfolios combinations of 1 to 4 instruments, Figure 74 shows the corresponding schedule risk of exceeding the 96-month requirement vs. the average cumulative delivered by the spacecraft after T_{life}= 2years of operations. Larger spacecraft (n_{inst} = 4) typically deliver a higher average cumulative utility than smaller spacecraft (n_{inst} = 1), consistent with the discussion conducted in section 3.6.2. On the other hand, the schedule risks associated with smaller spacecraft are found to be more limited (maximum schedule risk of ~37 %) than that of larger spacecraft (maximum schedule risk of ~ 91%). In other words, the confidence that the schedule constraint will be met is typically higher with smaller spacecraft than larger spacecraft.

Figure 75 allows a more detailed investigation by zooming in on the spacecraft portfolios that meet the schedule constraint with the 5 % confidence level.

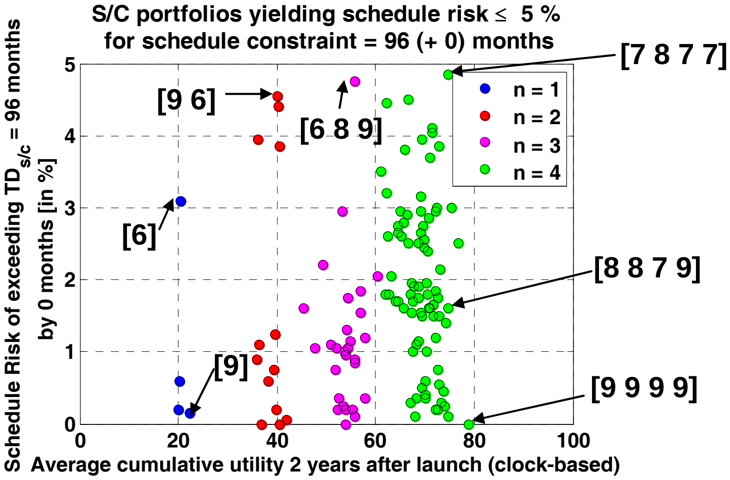


Figure 75. Spacecraft portfolios resulting in a schedule risk lower than 5 % for the 96-month delivery requirement.

Several observations can be made:

- Portfolios containing instruments with high TRLs do result in a lower schedule risk, in agreement with the comments made in section 3.5.1. Figure 75 allows the precise identification of the combinations that do and do not meet the 5 % schedule risk requirement.

- For portfolios containing $n_{inst} = 4$ instruments, any TRL lower than TRL 7 cannot be employed if the 96-month delivery requirement must be met with 5% confidence. This is not the case for smaller spacecraft, for which TRL 6 may be used in certain cases (increased design freedom).

Figure 76 represents the number of spacecraft portfolios meeting the 5 % schedule risk constraint as a function of the time remaining until the targeted launch opportunity. As the launch opportunity gets closer, the reduction in design freedom can be quantified. For example, at the very start of the development, there are 80 spacecraft portfolios of $n_{inst} = 4$ instruments that should still result in a time-to-delivery that meets the schedule requirement with a 5% confidence. This number drops significantly to ~12 two years later, that is, 6 years before the launch.

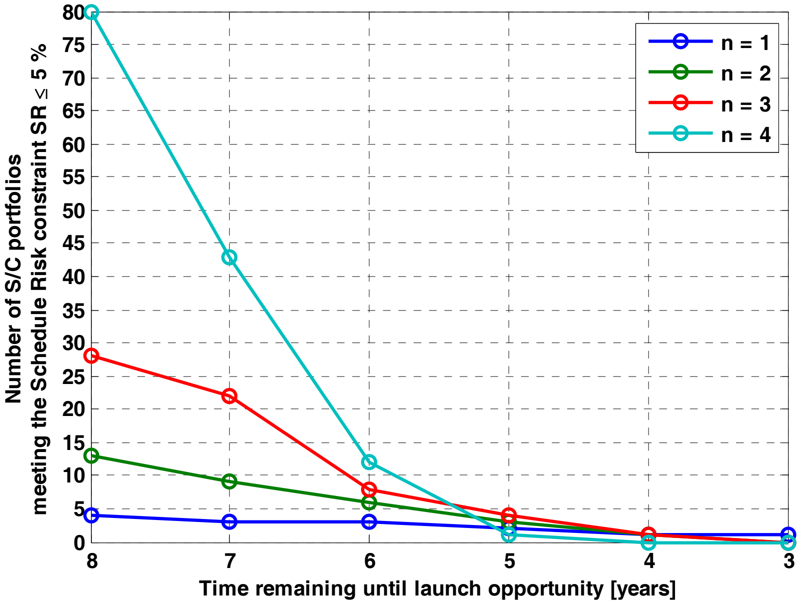


Figure 76. Number of spacecraft portfolios meeting the 5 % schedule risk constraint as a function of the time remaining until the targeted launch opportunity.

Several other observations can be made:

- Compared to small spacecraft portfolios, fewer large portfolios are possible as the launch date approaches. The larger size indeed results in the need for higher technology maturity in order to meet the launch date with a 5% schedule risk.
- If the launch is pushed back to the next opportunity (as a back-up plan), larger portfolios can still be considered and visualized as we have moved back along the left of the x-axis of Figure 76.

6.6.3.2 Defense scenario

This scenario considers the case of a series of Earth satellite missions that are highly focused (the number and nature of instruments is already determined) and for which no discontinuation of service as well as a maximal utility delivered is desired. Consider for example a new reconnaissance capability that is needed to monitor a region of interest (e.g., a country that is suspected to be developing weapons of mass destruction within a hypothesized time horizon). In that case, it is beneficial to be able to start collecting data as early as possible, i.e., as soon as the 1st satellite is delivered, and until the given time horizon, e.g. $\tau_{ops} = 15$ years. For this reason, the design space exploration is conducted in a calendar-based mindset.

Main requirements:

1. the first satellite must be delivered within the next five and a half years (soft deadline), i.e., $MTTD_{s/c} \leq 66$ months.
2. Two instruments are considered ($n_{inst} = 2$):
    - An imager in the visible spectrum

- A thermal infrared sensor to monitor nightly activities (such as the ones used onboard Advanced KeyHole-11 [204,205]).

Several candidate technologies with various levels of technology maturity, heritage, and performance are evaluated. Note also that instantaneous utility can be mapped into relevant quantities such as for example number of pictures taken per day and their quality (e.g., spatial resolution), etc.

Design decisions:

- What levels of technology maturity (TRLs) should be selected to ensure timely delivery as well as high performance?
- How often should the satellites be replaced (T_{life}) to minimize discontinuation of service and mitigate the effects of obsolescence?

Figure 77 represents the MTTD of the 1st satellite launched, for all the 2-instrument spacecraft portfolios and allows the identification of the ones that meet the $MTTD_{s/c} \leq 66$ months requirement. The corresponding possible combinations are listed in Table 12.

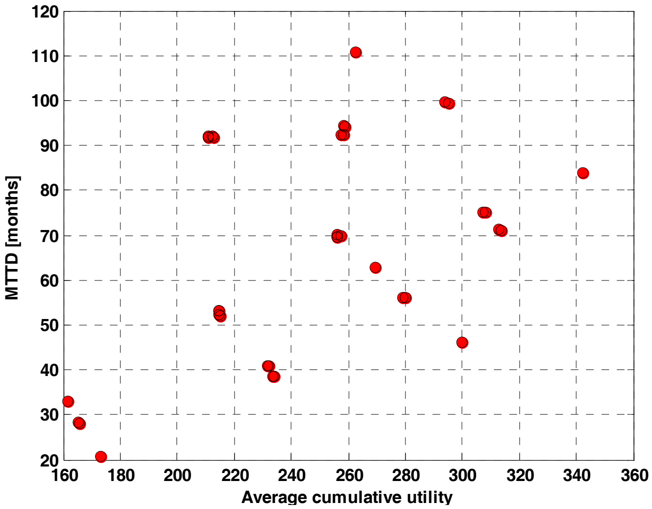


Figure 77. MTTD vs. average cumulative utility for all the various 2-instrument spacecraft portfolios, τ_{ops} = 15 years after development start (for the 1^{st} satellite of the series).

Note that spacecraft portfolios [i j] and [j i] are considered distinct since the two different instruments are distinct (by nature and function) and can thus be assigned different TRLs. Two different design choices are then captured. The resulting MTTD is however similar, within the accuracy of the model of spacecraft time-to-delivery. The analysis shows that only instruments of TRL greater or equal than 6 should be considered in the design in order to meet the schedule requirement.

For illustrative purposes, let us now compare only homogeneous spacecraft portfolios series for both ends of this TRL spectrum ([6 6] and [9 9] respectively). It is also assumed that **within a given series of spacecraft**, each spacecraft will have the same TRL configuration than its predecessor, with similar impact on instantaneous utility and time-to-obsolescence, and the same design lifetime T_{life}.

Table 12. Possible spacecraft portfolios combinations yielding $\text{MTTD}_{s/c} \leq 66$ months

Instrument 1 TRL	Instrument 2 TRL	MTTD (months)
6	**6**	62.9
6	**7**	56.0
6	**8**	53.1
6	**9**	52.2
7	**6**	56.2
7	**7**	46.1
7	**8**	40.8
7	**9**	38.6
8	**6**	53.3
8	**7**	40.9
8	**8**	33.0
8	**9**	28.2
9	**6**	52.1
9	**7**	38.7
9	**8**	28.2
9	**9**	20.7

For this scenario, the following model parameters have been selected:

- To capture the value of innovation, the instantaneous utility provided by a TRL 6-instrument that offers performance improvement has been set to $u_{0TRL6} = 2$, while the instantaneous utility provided by a TRL 9-instrument has been set to $u_{0TRL9} = 1$.
- For both the visible imager and the infrared sensor, the average time to minor obsolescence state (defined as the time of emergence of an alternative technology

that allows to improve the image resolution by a factor of 2) has been set to MTT(mO) = 8 years.

- For both the visible imager and the infrared sensor, the average time to major obsolescence state (defined as the time of emergence of an alternative technology that allows to improve the image resolution by a factor of 4) has been set to MTT(MO) = 15 years.
- The decrease in utility when an instrument is at the minor obsolescence state is captured by the coefficient $c_{mO} = 0.5$ that is multiplied to the instantaneous utility. Similarly, the decrease in utility when an instrument is at the major obsolescence state is captured by the coefficient $c_{MO} = 0.25$ that is multiplied to the instantaneous utility. The instantaneous utility delivered by a state-of-the-art instrument is then taken as the reference, i.e., $c_{SoA} = 1$.

Figure 78 represents the average cumulative utility delivered by each series of spacecraft ([6 6] or [9 9]) over a 15-year time horizon, as a function of the design lifetime T_{life} of each spacecraft.

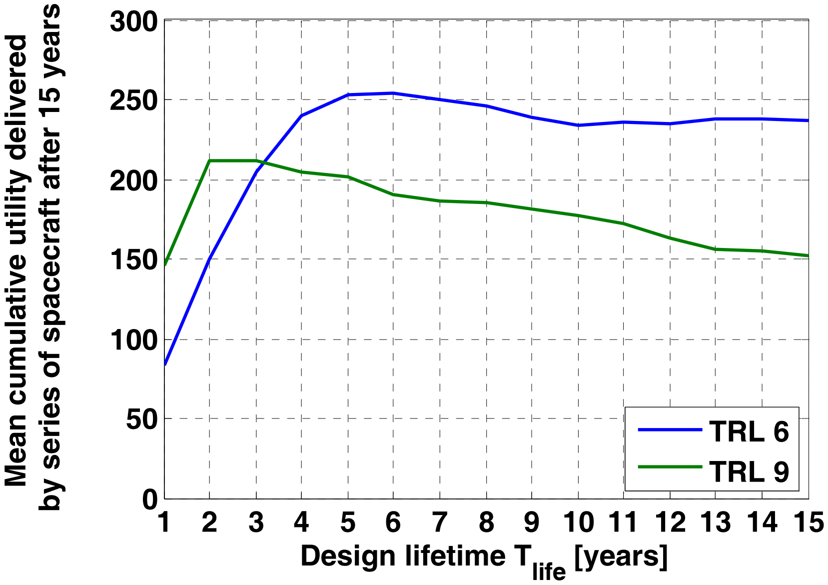


Figure 78. Mean cumulative utility delivered by a series of 2-instrument homogeneous spacecraft portfolios ([6 6] and [9 9] respectively) after τ_{ops} = 15 years

The analysis of Figure 78 shows how the choice of level of technology maturity (TRL) is contingent on the design lifetime considered. More specifically:

- **For T_{life} < 3 years, series of spacecraft portfolios using more mature technologies (TRL 9) deliver on average more utility over a time span of 15 years than series of low-maturity (TRL 6) spacecraft portfolios.**

  For those high-TRL portfolios series, the time-to-delivery of each subsequent spacecraft is relatively short, resulting in a rapid replacement of the previous spacecraft, thus guaranteeing a short (if any) discontinuation of service. In addition, the rapid turnover of spacecraft (short design lifetime T_{life}) allows more frequent technology refreshes, thus mitigating the impact of technology obsolescence.

- **For T_{life} > 3 years, series of spacecraft portfolios using more innovative but low-maturity technologies (TRL 6) deliver on average more utility over a time span of 15 years than series of high-maturity (TRL 9) spacecraft portfolios.**

  For those TRL 6-portfolio series, the innovative instruments offer performance improvements, resulting in a higher instantaneous utility delivered. No major discontinuation of service is experienced as the longer design lifetimes T_{life} allow for longer delivery schedules for the replacement spacecraft. As a result of those two effects, TRL 6-portfolio series provide a higher cumulative utility over the 15-year time horizon.

In this replacement scenario, optimal spacecraft portfolios series (on a utility basis) are therefore contingent on the design lifetime intended for each satellite, that is, the replacement frequency. Several technical and programmatic considerations (including cost) may lead towards the selection of one particular design lifetime. Outputs from the integrated model show that once this design lifetime is selected, there is a rational basis for the choice of the levels of technology maturity in the scenario described.

6.7 Summary

This chapter built on and refined the previous analyses developed in this thesis and presented an integrated framework that connected together the two main models presented in Chapter 3 and 5 (i.e., the model of spacecraft time-to-delivery and the model of on-orbit obsolescence). This complete framework allowed analyzing *jointly* the impact of design choices (materialized by the selection of portfolio characteristics) on the time-to-delivery $TD_{s/c}$, the time-to-obsolescence T_{obs} of the spacecraft, and the resulting implications in terms of cumulative utility delivered. This chapter then presented how the instantaneous instrument utilities could be tuned to capture the value of innovation as well as the impact of obsolescence. Results produced by the simulation tool/GUI developed for this thesis include schedule and utility outputs, full utility profiles for a given spacecraft portfolio and a series of spacecraft launched and replaced, based on the same portfolio configuration. Finally, two illustrative scenarios (science and defense missions) were investigated to show how the integrated framework developed in this thesis allows the exploration of the design space, the selection of design candidates based on the mission requirements, and the identification of trends to help conduct design trade-offs.

The next chapter summarizes the work conducted in this thesis and proposes new directions for future research.

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

> **“Hâtez-vous lentement ; et, sans perdre courage,**
> **Vingt fois sur le métier remettez votre ouvrage. ”**
> “Hasten slowly, and without losing heart,
> Put your work twenty times upon the anvil.”
>
> Nicolas Boileau-Despréaux, French poet
> *L'Art Poétique* (*The Art of Poetry*), Canto I, l. 171, 1674

7.1 Summary and contributions

This thesis explored the temporal dimension of what could be referred to as “programmatic systems engineering” in the case of space systems. Risk has many dimensions, and generally, cost risk and technical risks are explored in traditional systems engineering. This thesis focused instead on the less frequently explored “temporal risks” and investigated two types of temporal risk faced by space systems, namely schedule risk or risk of a late system delivery, and the risk of on-orbit obsolescence. The purpose of the thesis was twofold: 1) to first identify and develop a thorough understanding of the fundamental causes of the risk of schedule slippage and obsolescence of space systems; and 2) in so doing, to guide spacecraft design choices that could result in better control of spacecraft delivery schedule and mitigate those “temporal risks”.

It was hypothesized (Hypothesis 1 and 4 in the Introduction) that certain architectural choices made during the design of space systems may be key determinants of their responsiveness (or lack thereof), schedule slippage and risk of obsolescence. To explore these hypotheses, stochastic models of those temporal risks were formulated around selected design parameters such as the size or number of key subsystems or instruments of a space system (as a proxy for complexity), the technology maturity of each subsystem (as measured by the Technology Readiness Level or TRL), the heterogeneity of the technology maturity of the whole system, and the spacecraft design lifetime. Furthermore, essential conceptual questions were contemplated in the form of Hypothesis 2 and 3: can we conceive of and analyze a spacecraft as a portfolio of technologies? What implications would this have in terms of schedule risk, and what design choices can it help inform? To what extent, if any, is the current spacecraft design and optimization paradigm (clock-based) responsible for the issues of schedule slippages experienced in the space industry, and can an alternate paradigm be formulated to address these issues?

These various research questions were motivated and investigated throughout each chapter of this thesis:

Chapter 2 discussed the importance of responsiveness for the space industry, and provided **a review and synthesis of the literature on responsive space** and the challenge of keeping the development of space systems on schedule. **A multi-disciplinary framework was provided for thinking about and addressing issues of space responsiveness**: it defined different levels or types of responsiveness (global, local and interactive), introduced tools for identifying and prioritizing responsiveness-improvement efforts (such as time compressibility metric and responsiveness maps), and identified “levers of space responsiveness” or practical means for improving space responsiveness. These include launch levers (vehicles and ranges), “soft” levers of responsiveness (selection processes, design reviews, acquisition policies, export control laws), and design-centric levers (modularity, complexity, technology maturity).

Chapter 3 then addressed the limitations of the TRL scale at the system-level and explored the effects of other design parameters on spacecraft delivery schedule. To do so, Chapter 3 adapted the notion of portfolio developed by the R&D community to the micro-level of a single complex engineering system**.** Chapter 3 thus proposed to **conceive of and analyze a *spacecraft* as a portfolio of technologies/instruments**, whose characteristics were defined as the spacecraft size (e.g., number of instruments), the technology maturity of each instrument, and the resulting TRL heterogeneity of the portfolio. Chapter 3 introduced **a stochastic model of spacecraft time-to-delivery constructed around the concept of spacecraft technology portfolio**. This model explicitly estimated the duration of the Instruments development, the spacecraft Integration and Testing, and the spacecraft Shipping phases, by treating the respective durations as random variables. The resulting random variable Time-to-Delivery (along with its mean and dispersion) constituted one important characterization of space responsiveness and schedule risk. Through the variation of the portfolio characteristics, Chapter 3 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. Finally, the utility implications of varying the portfolio characteristics and time-horizons were explored, and “portfolio maps” were provided as guides to help system designers identify appropriate portfolio characteristics. Chapter 3 identified **a critical paradigm shift needed for designing for responsiveness**, by opposing the traditional clock-based mindset (in which utilities are calculated and compared after the launch) to a calendar-based environment (i.e., for a given time-horizon after the start of development). Chapter 3 emphasized the importance of clearly identifying which temporal mindset is more appropriate for a given situation (clock-based or calendar-based).

Chapter 4 then presented another type of “temporal risk” faced by systems (including spacecraft), namely the risk of obsolescence, which has several implications after the system is produced (from a cost and utility standpoint). The purpose of Chapter 4 was to **help improve the understanding of the phenomenon of obsolescence and to unveil its fundamental causes**. It was showed that obsolescence involves *the relationship* of a stakeholder to the product over time, in a given environment, and was then formally defined as “the decline of value of a product over time, due to a change in the stakeholder’s expectations resulting from exogenous events”. Four main drivers of obsolescence were then identified: technological innovation, network externalities, regulatory changes and need disappearance. Finally, Chapter 4 examined **how obsolescence has been traditionally approached and modeled in various disciplines**, namely in economics, operations research, bibliometrics and engineering. Through this review, two main perspectives emerged: a decline-focused perspective, reflecting the rate of decline of product value over time, and an instant-focused perspective, reflecting the instant at which obsolescence starts or onset of obsolescence. The issues and notions discussed in Chapter 4 paved the ground for the modeling of obsolescence of space systems conducted in Chapter 5.

Chapter 5 shed some new light on the divergence of views concerning best practices for the design and development of space systems in relation to obsolescence and technology maturity. In several of its reports, the U.S Government Accountability Office recommended the inclusion of only mature technologies in acquisition programs, specifically with a TRL ≥ 7, in order to limit the likelihood of cost growth and schedule slippage. Although still committed to limiting the probability of cost overruns and schedule slippages, the U.S Department of Defense raised concerns about the likelihood of deploying space assets that may become rapidly obsolete on orbit. This reason can partially explain why the use of low-maturity technologies in acquisitions programs has persisted within the DOD. Chapter 5 proposed to provide new analytical answers to this argument (formulated by Hypothesis 4), by introducing **the concept of "Risk of On-Orbit Obsolescence"**, a unique form of obsolescence faced by space systems resulting from their specificities (physical non-accessibility, long development schedule and extended design lifetimes). Specifically, **a stochastic model of Risk of On-Orbit Obsolescence based on two Markov models was developed**: 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. Three types of risks of on-orbit obsolescence were defined from the interaction of those two models: a Static Risk of On-Orbit Obsolescence (SRO) that represents the *overall* risk that the spacecraft used over a given time-horizon will be obsolete while being on orbit; a (dynamic) Lifetime Risk of

On-Orbit Obsolescence (LRO) that informs about the instantaneous probability that a spacecraft will be obsolete at a given instant after it has been launched; finally a (dynamic) Calendar Risk of On-Orbit Obsolescence (CRO) that represents the instantaneous conditional probability of the spacecraft of being obsolete, provided it is on orbit, at a given calendar date. These two definitions emphasized the importance of clearly defining the temporal mindset in which one operates to assess the evolution of the risk of obsolescence over time.

Finally, Chapter 6 proposed to go beyond the initial system-centric evaluation of obsolescence of Chapter 5, by modeling the obsolescence phenomenon at the instrument (or subsystem) level. More importantly, it presented **an integrated modeling framework that connects the instrument-centric obsolescence model to the model of spacecraft Time-to-Delivery** based on the idea of spacecraft portfolio presented in Chapter 3. The resulting framework provided **a powerful capability to simultaneously explore the impact of design decisions on spacecraft schedule, on-orbit obsolescence, and utility delivered over time**. Figure 79 illustrates the new optimization horizons, or "augmented temporal dimension", opened by this thesis, that the integrated framework of Chapter 6 proved capable of exploring. When the design space is traditionally explored, many optimization tasks are typically conducted

a. deterministically

b. in a clock-based mindset that does not account for the time-to-delivery of the spacecraft (as discussed in Chapter 3) and

c. without reflecting the actual change of utility delivered by the spacecraft over time that results from on-orbit obsolescence or on-orbit failures.

The new design mindset introduced in this thesis is

d. stochastic, allowing the modeling of (various) uncertainties

e. calendar-based (when appropriate); in other words, it accounts for the time-to-delivery of the system

f. capable of capturing changes of utility delivered by the spacecraft over time, resulting from temporal risks occurring during the lifetime of the spacecraft, such as on-orbit obsolescence or on-orbit failures, etc.

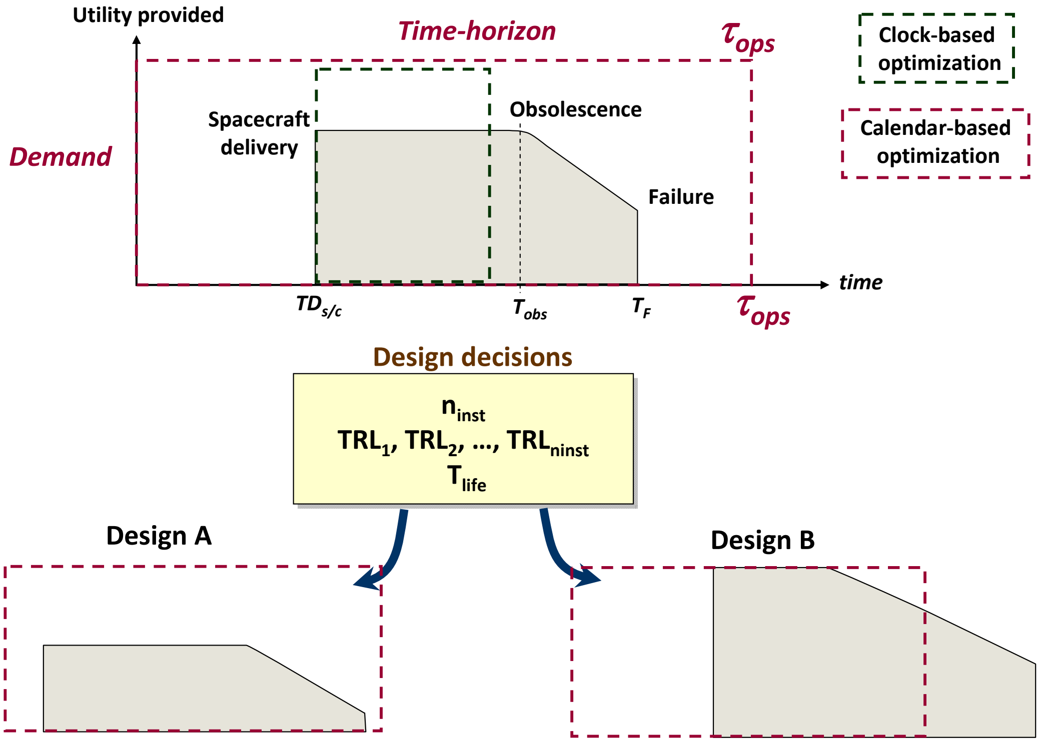


Figure 79. Calendar-based optimization of utility delivered under the risk of late delivery, on-orbit obsolescence and on-orbit failures (notional)

In this new design mindset, various combinations of the design parameters values or spacecraft portfolio characteristics will yield different utility profiles over time (with different time-to-delivery $TD_{s/c}$, time-to-obsolescence T_{obs} and time-to-failure T_F). As illustrated in Figure 79, some designs may result in a late delivery but a later onset of obsolescence, while some others may result in a shorter delivery but a more rapid obsolescence.

In conclusion, the integrated framework fulfills the premise of the thesis of modeling and analyzing the temporal risks faced by space systems to help inform design decisions. The integrated framework allows the exploration of design options along this "augmented temporal dimension" and the identification of system design choices that satisfy various constraints and objectives, temporal (delivery times/dates) as well as utility-based.

7.2 Review of hypotheses

This section now revisits the hypotheses formulated in Chapter 1, in the light of the results obtained by the models presented throughout this dissertation.

7.2.1 Hypothesis #1

In addition to programmatic considerations, architectural choices and design parameters are key determinants of spacecraft delivery, schedule slippage and responsiveness (or lack thereof).

As a preliminary test of Hypothesis 1, Chapter 2 focused on one design-centric lever of responsiveness, namely the Technology Readiness Level. The univariate statistical analysis of schedule as a function of average system-TRL suggested that the **overall level of technology maturity characterizing a space system at the start of its development has significant implications on schedule slippage and schedule risk**. Specifically, it was shown that the average and dispersion of the schedule slippage increases when the system-TRL decreases, that is, with the use of low technology maturity.

The results of the Monte-Carlo simulations of the stochastic model of spacecraft time-to-delivery formulated in Chapter 3 then 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**.

7.2.2 Hypothesis #2

Conceiving of and analyzing a spacecraft as a technology portfolio (of instruments/subsystems) will reveal insights about spacecraft delivery schedule and responsiveness, and will help make better risk-informed design decisions (in particular with respect to schedule risk).

Analyzing a spacecraft as a technology portfolio highlighted the combined effect of the instruments TRL and the number of instruments on schedule and responsiveness. Specifically:

- The sensitivity of the MTTD to TRL increases when the number of instruments increases.

- The impact of an increase in number of instruments on MTTD is more significant at low TRL than at high TRL.

TRL-schedule risk curves were then introduced to **visualize and quantify schedule risk changes as a function of the spacecraft portfolio parameters.** Finally, **the MTTD was found to decrease as the heterogeneity of the technology maturity characterizing the portfolio** (measured by the degree of TRL-heterogeneity) **decreases.**

7.2.3 Hypothesis #3

The current clock-based design optimization mindset is one major driver of the recurrent issues of schedule slippage.

To address Hypothesis 3, Chapter 3 showed that the use of the clock-based optimization mindset results in the **promotion of design choices that may ultimately jeopardize space responsiveness**. Specifically, under the clock-based paradigm that does not account for the spacecraft delivery time, bigger spacecraft appear to deliver the most cumulative utility over time, **despite being characterized by longer development schedules**. On the other hand, **under the calendar-based paradigm, optimal spacecraft portfolio (on a utility basis) are contingent on the time horizon of interest**. For example, when operating in a calendar-based environment, 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.

This comparison demonstrated that **optimal design choices are different depending on the optimization mindset adopted**. In particular, the calendar-based paradigm proved relevant to design for space responsiveness as it accounts for the time-to-delivery of the spacecraft.

7.2.4 Hypothesis #4

The risk of on-orbit obsolescence is influenced by architectural choices and design parameters, and a trade-off exists between mitigating the risk of on-orbit obsolescence and schedule risk.

It was shown that **the overall risk that the spacecraft (or its instruments) becomes obsolete while it is on orbit**, or static risk of on-orbit obsolescence (SRO), **is reduced when the spacecraft design lifetime is reduced**.

When observed over the entire lifetime of the spacecraft (via the Lifetime Risk of On-Orbit Obsolescence), it was then found that the risk of obsolescence is no more significant at high TRL than at low TRL. On the other hand, **it was shown that when focusing on a given calendar date (via the Calendar Risk of On-Orbit Obsolescence), a lower initial risk of obsolescence may be obtained with low maturity technologies, provided the spacecraft is delivered early enough**.

Finally, **obsolescence-schedule risk plots** were introduced to explore situations in which **a trade-off exists between schedule risk and the calendar risk of on-orbit obsolescence**. Specifically, they allowed visualizing simultaneously the reduction of CRO and the increase of schedule risk with the use of lower technology maturity.

7.3 Flexibility of the modeling framework

The complete framework developed in this thesis possesses flexibility that manifests itself on various levels, as discussed below and summarized in Table 13:

- The modeling framework formulated in this work was applied to space systems, but is relevant to any complex engineering system that can be conceived of and analyzed as a portfolio of technologies.

- A spacecraft “instrument” was considered the elementary constituent of the spacecraft portfolio, as it corresponds to an independent value-delivering subsystem of the spacecraft. This choice was motivated by the numerous analyses conducted in this work that focused on the utility provided by the spacecraft over time. Nevertheless, the framework remains valid if a more general definition of the spacecraft portfolio constituents is adopted, in which the main spacecraft subsystems in a broader sense (and not limited to payload instruments) are used.

- Each portfolio instrument follows an individual technology maturation path, as well as an individual obsolescence path. While for each instrument, the states and transitions describing these paths were assumed to be identical (for the sake of simplicity), they need not be the same for each instrument. For example, technologies related to thermal systems may mature at a different pace than technologies related to structural systems. In other words, the specificities of a subsystem or instrument i can call for a “specialization of the path” to be followed by instrument/subsystem i. This can be performed by the addition or removal of states, and/or the use of specific temporal transitions that are deemed more appropriate for subsystem i.

- State transitions and enabling conditions (the "wiring" between the states) can be rearranged to reflect the degree of coupling between the various instruments/subsystems developments. For example, the complete maturation of one instrument may be contingent on the advancement of the development of another subsystem. The level of interdependence of the developments of each portfolio constituent constitutes an important modeling opportunity enabled by the framework flexibility.

- Any well-defined period of the spacecraft lifecycle (whether it is during the development phase or during the operations phase) with a distinct and inherent amount of uncertainty can be defined as an individual state. Specifically:
    - The Integration & Testing, and shipping phases can be broken down into more elementary stages (and therefore states), provided schedule data is available to support the definition of the corresponding transitions
    - Additional states of obsolescence can be added to represent a more gradual decline of value
    - Each obsolescence state can be unfolded into different obsolescence states related to various drivers of obsolescence (e.g., technology innovation and standardization being treated as two separate sources of obsolescence), and thus governed by different dynamics.

- While the Technology Readiness Level (TRL) metric was used to measure the advancement of the technology maturation process and to index the probability distributions of schedule, any other metric of technology readiness could be implemented to complement or substitute the use of the TRL.

Table 13. Summary of the flexibility features of the framework developed in this thesis

Characteristic	Flexibility feature
Relevance	Framework relevant to any complex engineering system that can be conceived of and analyzed as a portfolio of technologies
Spacecraft portfolio constituents	“Payload instrument” can be replaced by spacecraft subsystems in a broader sense
Temporal paths	Distinct temporal paths adapted to each portfolio constituent (subsystem or instrument) can be defined
Modeling structure	State transitions and enabling conditions can be rearranged to reflect different levels of dependence between the subsystems/instruments developments
State-based representation	Number of states can be modified based on scope of the analysis and data availability
Metrics	Any relevant metric of technology readiness can be implemented to complement or substitute the use of the TRL metric

7.4 Recommendations for future work

7.4.1 Data collection

Limited TRL and schedule data is currently available to academia. Extensions to the work proposed in this thesis would highly benefit from an extended dataset to define transition laws guiding the technology maturation process as well as the subsequent phases of spacecraft development (e.g., integration and testing, shipping). This thesis advocates a systematic methodology to record and document the schedule of space projects in relation with design parameters including:

At the mission level:

- Projected dates of main reviews (such as Concept Study Report, Mission Design Review, Systems Requirement Review, Preliminary Design Review, Critical Design Review, Flight Readiness Review, etc.), key decision points and launch
- Actual dates of main reviews, key decision points and launch

At the subsystem level:

- For each subsystem and payload instrument, initial TRL at a date defined as the starting point (Authority-to-Proceed, contract award, etc.)
- For each subsystem and payload instrument, projected date of the consecutive transitions to the next TRL
- For each subsystem and payload instrument, actual date of the consecutive transitions to the next TRL

While this methodology may already be implemented (at least partly) in the industry or within government agencies like NASA and DOD, access to consistent data required for any modeling and analysis task remains limited. The Cost Analysis Data Requirement (CADRe) initiative started by NASA in 2003 constitutes one step in that direction [206]. The guidelines for the responses to the Request For Information of the Astro 2010 Decadal Survey made the comparisons presented in section 6.2.5 possible. It is the author's wish that such recommendations become generalized to all proposals and documentation pertaining to the design and development of space systems.

7.4.2 Beyond the limitations of the TRL metric

Many models presented in this thesis used the TRL metric as a yardstick to estimate the duration of the development of subsystems (and more specifically, instruments) and of the entire spacecraft. Since its formulation within NASA in the 1980's, various limitations of the TRL metric have however been identified, such as its intrinsic ambiguity [59,196,207]. Not only the sources of information may differ to evaluate the TRL of one technology, but also the interpretation of the information remains at least partly subjective, resulting in possible discrepancies in the TRL assessment of that technology. In an effort to overcome this obstacle, the Air Force Research Laboratory developed a TRL Calculator to provide some guidance in the evaluation of the TRL of a technology [208]. Through various questions asked to the user about to the current status of the technology considered, AFRL's TRL Calculator follows a systematic algorithm to determine the current TRL of the technology. Despite its explicit attempt to provide a rational basis for the assessment of a TRL, the TRL Calculator does not provide one unique and absolute answer as the user can choose to weight differently the various categories of questions asked. This raises the point that the residual ambiguity of the TRL scale may never be eliminated, even by the most accurate and systematic assessment tools.

It could be argued that part of the resulting uncertainty related to the ambiguity of the TRL may already be captured by the random nature of the schedule estimates indexed by TRL discussed in this thesis. However, one possible research direction to explore this further would be to attribute *uncertainty to the TRL value itself*. It is precisely the discrete nature of the TRL scale that makes it difficult to assign a TRL value to a technology whose maturity (or readiness level) may in actuality lies somewhere in between two values. Note that an intrinsic “fuzziness”, inherent to the difficulty of mapping subjective statements on technology maturity to numbers, may remain regardless of the metric (TRL or other) used to index the probability distributions describing the random variables of schedule. This fuzziness characterizing the level of maturity of a technology has to be distinguished from the “random” nature of the schedule estimates that have been indexed by the TRL (which results from unexpected, random events associated with technical, organizational, budget difficulties). In other words, it seems inadequate to consider that the level of maturity of a technology is “randomly” distributed between various values.

In the light of these considerations, fuzzy theory may constitute a possible research direction to model the “fuzziness” of the maturity of one technology with respect to the 9-level TRL scale commonly accepted.

Fuzzy sets were introduced by Zadeh in 1965 [209] to extend our ordinary concept of sets and have since then generated significant interest in the field of mathematics and found numerous applications in engineering, medicine, decision making, social sciences, etc. Traditional subsets A on a referential set E (e.g., **R, Z** or **N)** are called *crisp sets* and are typically represented by their characteristic function μ_A that takes its values in {0,1}, as follows [210]:

$$\forall x \in E \quad \begin{array}{l} \mu_A(x) = 1 \text{ if } x \in A \\ \mu_A(x) = 0 \text{ if } x \notin A \end{array} \tag{7.1}$$

An ordinary number a is a crisp set reduced to a singleton {a}.

A fuzzy set A can be defined through its membership function μ_A, which, unlike the characteristic function of crisp sets formulated in Boolean algebra, takes its values in the entire interval [0,1]. (Crisp sets can thus be considered a special case of fuzzy sets). In other words, in traditional set theory, an element either belongs to the crisp set or does not. Figure 80 shows that an element can belong to a fuzzy set with various degrees of membership (described by the membership function).

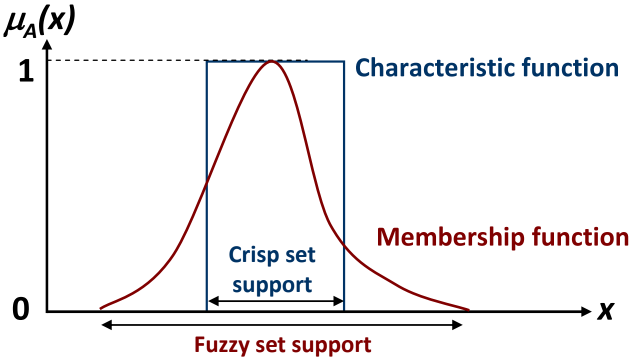


Figure 80. Crisp set and fuzzy set (notional)

Kaufman and Gupta then define a *fuzzy number* as a fuzzy set whose membership function is convex and normal (i.e. the maximum value of the fuzzy set is 1) [210].

Those concepts may prove useful to capture the intrinsic ambiguity of the TRL scale and the inherent subjectivity of TRL assessment. Instead of considering the TRL value of a given technology an ordinary number, it can be represented by a fuzzy number.

For example, the proposition "TRL ~ 4" could be expressed by a fuzzy number such as the one represented in the left panel of Figure 81. The proposition "TRL ~4-5" could be expressed by a fuzzy number such as the one represented in the right panel of Figure 81.

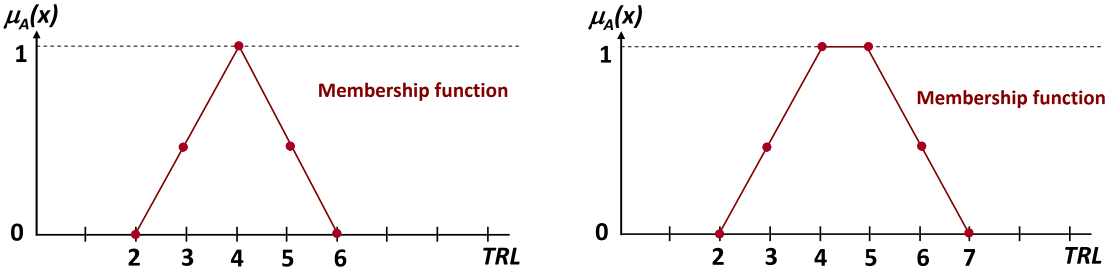


Figure 81. Possible Triangular Fuzzy Number (TFN) representation of TRL ~ 4 (left) and possible Trapezoidal Fuzzy Number (Tr.FN) representation of TRL ~ 4-5 (right)

Expert elicitation can be used to provide different estimations of the TRL of each technology. Several techniques have been proposed to create the fuzzy number resulting from the aggregation of each expert contribution [211], including the Fuzzy Delphi Method (F.D.M) [212].

Once a membership function has been defined for each technology of the spacecraft portfolio, one important task that remains is to find the proper definition of the probability density function describing the time-to-delivery of the spacecraft that is indexed by the fuzzy number associated to the technology. The fields of fuzzy sets (or "possibility theory") and probabilities are rich in concepts and analytical tools that could serve this endeavor if combined together.

7.4.3 Further investigation of time to system integration and testing

The integrated framework proposed in Chapter 6 uses probability distributions for the random variable time-to-integration and test T_{int} similar to those presented in section 3.4.2. These lognormal distributions were indexed by the portfolio characteristic number of instruments n_{inst}, with larger spacecraft portfolios having longer average integration and testing times and higher variability in that variable. It is worth exploring further the different architectural and technical factors involved in the integration and testing phase. Specifically, one could consider to “unfold” the I&T state of the integrated framework (see Figure 69) to exhibit the different interactions between subsystems/technologies. In that case, a metric similar to the IRL metric discussed in section 2.7.2 could serve as a yardstick to model the integration of various combinations of instruments (or subsystems), in the same way that the TRL metric was used to index the probability distributions of instrument delivery schedule. This constitutes an important area of further improvement of the current framework, provided that data that relates IRL (or any other integration metric) to the duration of the integration and testing phase can be collected in the future.

7.4.4 Impact of resource allocations

The analyses conducted for this thesis were made with the assumption that resources (e.g., budget, workforce) were fixed. Recall the compressibility metric defined in section 2.4.1 :

$$\beta \equiv -\frac{1}{\tau_0}\frac{\partial \tau_0}{\partial r} \tag{7.2}$$

Through the definition of β and the formulation of responsiveness maps, Chapter 2 identified resources as a key factor impacting responsiveness. The integrated framework presented in Chapter 6 could be extended to include for example a variable representative of the budget allocated to the project. Ramirez-Marquez and Sauser [58] addressed a similar problem and proposed an approach based on the IRL and SRL metrics (discussed in section 2.7) and the estimation of resource consumption for each integration effort (i.e., cost and time needed to transition from TRL j to TRL j+1 and from IRL k to IRL k+1). Their approach allows for the prediction of the maximum maturity that can be reached based on the resources allocated to the project. Recall that this thesis was concerned with the modeling of the spacecraft time-to-delivery, and assumed that systems are deployed once full maturity is reached. In this situation, the use of the compressibility metric β at several stages of the lifecycle of the spacecraft (e.g., instruments development, integration & testing) could provide an opportunity to change the transition probabilities (i.e., the duration of the transition) from one state to the next, as a function of the allocated budget.

This refinement could be performed in two ways:

- in a static manner: the budget is assumed to be allocated at the start of the development and remains constant over time.
- in a dynamic manner: the budget fluctuates according to funding profiles that "update" the transition probabilities in real time.

This thesis recognizes the importance of resource allocation for responsiveness and considers this issue an important research direction for future work. The relevance and validity of any modeling effort of resource impact on responsiveness (captured through expediting maturity transitions for example) will be contingent on the availability and collection of the appropriate data.

7.4.5 Implications of on-orbit obsolescence

In Chapter 6, the impact of obsolescence was modeled via a reduction of the instantaneous utility delivered by the instruments going obsolete. As highlighted in Chapter 5, obsolescence is a significant problem for space systems, and presents major consequences that extend beyond the reduction of utility delivered. Several directions can be explored to refine the modeling of obsolescence and its implications for the design of space systems. Because ground systems are so tied to technologies that are flown onboard a spacecraft, there exists a cost and time penalty in upgrading technologies on the ground to support future spacecraft using innovative technologies. The cost dimension was not explored in this thesis; there are however opportunities to model the implications of on-orbit obsolescence in addition to the reduction of utility. The issue is particularly relevant when using the integrated framework for a series of spacecraft (through consecutive replacements, as illustrated in section 6.6.3.2), and further refinements could include:

- Extending the integrated framework to include ground nodes as part as the total system delivering utility. Those ground nodes would also face obsolescence, but unlike spacecraft, could be upgraded to restore modernity. In a state-based representation, this would correspond to the modeling of a transition from an obsolescence state to the State-of-the-Art state, with a "time-to-restore" of the ground node. The delivery of utility could result from the joint operation of spacecraft instruments and ground nodes.

- Revising the replacement policy presented in section 6.4.2 to capture the time penalty of upgrading technologies on the ground. For example, if instrument *j* on spacecraft of generation#1 becomes obsolete while it is on orbit, it can be decided to upgrade the ground installations to accommodate a new type of technology for instrument *j* of the replacement spacecraft (generation #2). Completion of the technology refresh of the ground installations could be modeled as an enabling condition for the development of the replacement spacecraft, thus potentially increasing its time-to-delivery.
- To explore the cost dimension, costs can be assigned not only to each transition of the spacecraft development module (instruments development, integration & testing, shipping), but also to the upgrades of ground installations. Such transitions can be activated only if the cost profile of the entire system {ground + spacecraft} remains under the resource profile proposed in section 7.4.4. In other words, the use of state-of-the-art technologies for replacement spacecraft (which was an assumption of the integrated framework), could be contingent on the difference between available resources and upgrade costs.

7.4.6 Concurrent development of design alternatives and implications for spacecraft time-to-delivery

The integrated framework currently uses a single design as a starting point. In other words, a single spacecraft portfolio gets carried over throughout the various states constituting the development and operations modules. The current model could be extended to concurrently consider alternate technology options that represent "design contingency plans" or "design backup paths". The impact of the pursuit of simultaneous design alternatives on the responsiveness of the delivery of capability can then be assessed.

For example, spacecraft portfolio **Pf** = [4 9 7 9] is being developed but program managers decide to also pursue the development of an alternate instrument #1 at TRL = 6 instead of TRL = 4. If technical difficulties emerge, resulting in the excessive consumption of resources (budget and/or time), managers may decide to replace the TRL-4 instrument by the TRL-6 instrument in the initial design. What are the time savings associated with the adoption of this “contingency plan”? What are the potential difficulties (and thus time penalties) that may emerge from a systems engineering perspective, if the design must now accommodate the TRL-6 instrument? Those are questions that can be further explored if concurrent development of design alternatives is investigated.

APPENDIX A: LOGNORMAL PROBABILITY PLOTS FOR THE MODEL OF SPACECRAFT TIME-TO-DELIVERY

This appendix provides a justification of the use of lognormal distributions for the three main modules of the model of spacecraft time-to-delivery developed in Chapter 3, namely the model of Instruments Delivery Schedule [Eq. (3.2)], the model of Integration & Testing Schedule, T_{int} [Eq. (3.6)], and the model of the spacecraft shipping time T_{ship} [Eq. (3.8)].

To test the appropriateness of lognormal distributions for these schedule-related random variables, the data is here displayed 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 [213,214], and the specifics of Weibull probability plots are discussed in a paper by Castet and Saleh [215]. For each of the three modules of the model of spacecraft time-to-delivery $TD_{s/c}$, the lognormal probability plots are provided in the following sections, based on the data available (limited in some cases) to justify the use of lognormal distributions as good approximation for the input random variables.

Integration & Testing phase duration

Figure 82 shows lognormal probability plots for the data set of 21 NASA spacecraft used in section 3.4.2 to model the duration of the Integration & Testing phase. When all portfolio sizes are considered, the left plot of Figure 82 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 (3.6) and (3.7). For example, consider the case $n_{inst} = 3$ instruments: for this subset of spacecraft, the right plot of Figure 82 provides a lognormal probability plot that shows a good alignment of the data along the lognormal line.

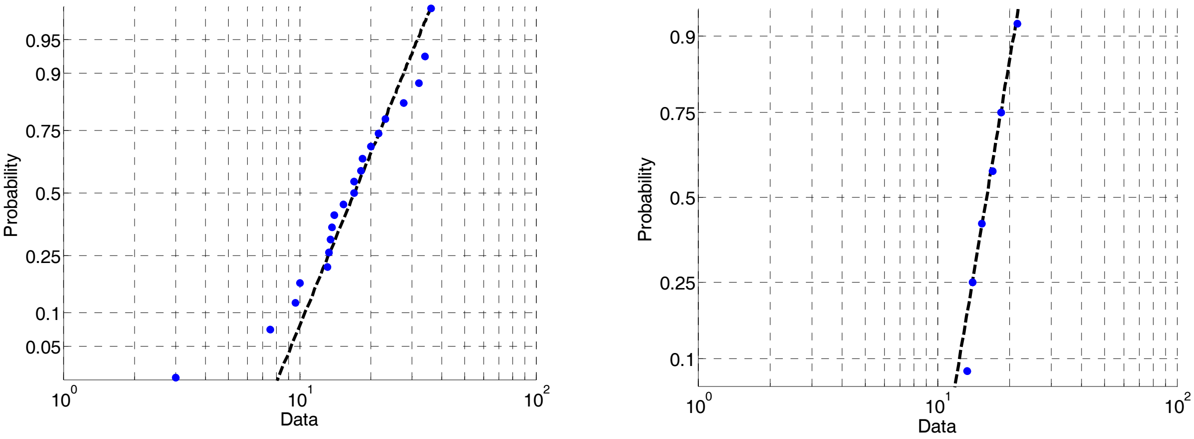


Figure 82. Lognormal probability plot for duration of Integration & Testing (left: all portfolio sizes; right: only $n_{inst} = 3$)

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 thesis, but they would constitute useful future work if a larger dataset was available.

Spacecraft Shipping phase duration

In section 3.4.3, the duration of the shipping phase was modeled using a single lognormal distribution. Figure 83 shows the corresponding lognormal probability plot for the 21 spacecraft of the dataset. The data seems roughly aligned for the larger durations; a noticeable divergence from a pure lognormal distribution is however 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 thesis.

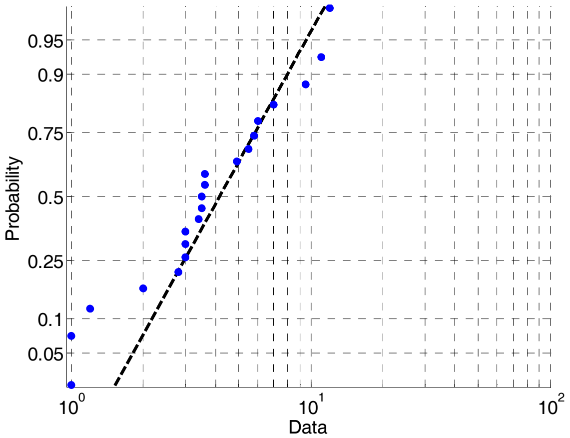


Figure 83. Lognormal probability plot for duration of Shipping

To confirm the visual inspection of Figure 83, a Kolmogorov-Smirnov goodness of fit test can be performed. The set used to calibrate the model of shipping time included m = 21 data points. The Kolmogorov-Smirnov statistic is:

$$D_m = \sup_t \left| F_m(t) - F(t) \right| \tag{A.1}$$

where F_m represents the empirical cumulative distribution function of shipping time (i.e., from the dataset) and F is the underlying cumulative distribution function. In section 3.4.3, the modeled cumulative distribution function was chosen to be described by the lognormal function of Eq. 3.8. Figure 84 shows both cumulative distribution functions, from the data (empirical) and from the model of shipping time.

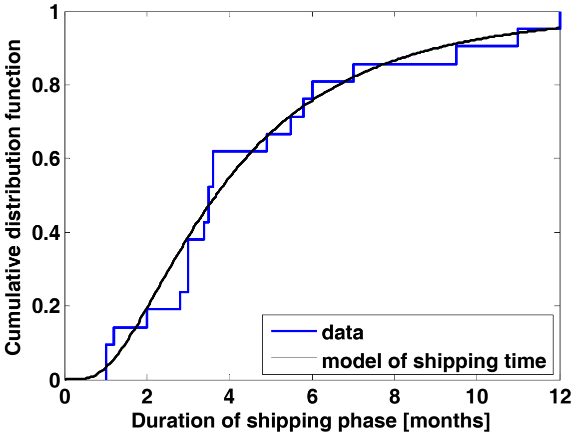


Figure 84. Comparison between the empirical cumulative distribution function from the data and the cumulative distribution function of the model of shipping time

For each "step" of the empirical function, the Kolmogorov-Smirnov test considers the difference between the value of the model c.d.f and the upper and lower values of the empirical c.d.f. The resulting statistic is the maximum of all those differences. With the 21 data points from the sample and the inferred distribution of Eq. 3.8, the Kolmogorov-Smirnov statistic for the duration of the shipping phase is found to be D_m = 0.1593. For m = 21, tables of Kolmogorov-Smirnov critical values [203] show that for a level of confidence $1-\alpha = 0.90$, the null hypothesis that the underlying c.d.f $F(t)$ is the modeled function is not rejected.

In conclusion, while it is not claimed herein that the 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.

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 section 2.6.1 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. The left plot of Figure 85 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, the right plot of Figure 85 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.

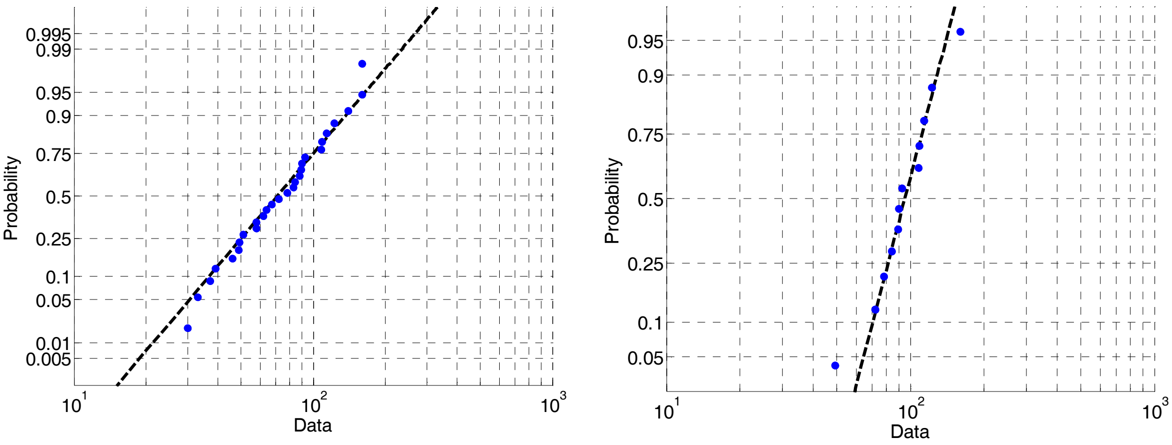


Figure 85. Lognormal probability plot for total schedule (left: all TRLs; right: only systems with system-TRL = 5)

APPENDIX B: ALGORITHMIC STRUCTURE

In an effort to enhance the transparency of the study conducted for this thesis and to facilitate the replication of the results, this appendix now presents the algorithmic structure of the main functions and scripts used to perform the calculations and analysis presented previously.

The following list describes the different input and output variables used by the main scripts and functions:

τ_{ops} = time-horizon of a calendar-based analysis

dt = time step of the simulation (here, dt = 1 month)

T_{clock} = time span of a clock-based analysis (after launch)

n_{cases} = number of Monte-Carlo cases

n_{inst} = number of instruments or portfolio size

c_{SoA} = obsolescence coefficient for utility delivered at State-of-the-Art state

c_{mO} = obsolescence coefficient for utility delivered at minor Obsolescence state

c_{MO} = obsolescence coefficient for utility delivered at Major Obsolescence state

Risk level = Risk level for schedule risks as described in section 3.4.7

Pf = spacecraft portfolio vector as described in section 3.4.1.2

$\hat{u}_0$ = instantaneous utility vector as described by equation 6.12

T_{life} = spacecraft design lifetime

$MTT(SoA_i \rightarrow mO_i)$ = mean-time-to-minor Obsolescence from SoA for instrument i

$MTT(SoA_i \rightarrow MO_i)$ = mean-time-to-Major Obsolescence from SoA for instrument i

$MTT(mO_i \rightarrow MO_i)$ = mean-time-to-Major Obsolescence from mO for instrument i

β_i = shape parameter for failure model of instrument i

θ_i = scale parameter for failure model of instrument i

$TD_{s/c}$ = spacecraft time-to-delivery (random variable)

$MTTD_{s/c}$ = spacecraft Mean-Time-to-Delivery
$u_j(t)$ = utility profile delivered by instrument j
$u_{SC}(t)$ = utility profile delivered by entire spacecraft
$u_{SC}^{k}(t)$ = utility profile delivered by spacecraft of generation k
$u_{SC}^{series}(t)$ = utility profile delivered by series of spacecraft
t^{*}_{k} = instant of development start (or ATP) of spacecraft of generation k
$\delta(Pf)$ = degree of TRL-heterogeneity of portfolio Pf
μ_{TRL} = average TRL of a spacecraft portfolio
$utot_{SC}$ = total cumulative utility delivered by a spacecraft

Basic simulation for a given spacecraft portfolio configuration

Figure 86 represents the structure of a basic simulation for a given portfolio Pf, using the integrated framework from command line or Graphical User Interface (presented in section 6.5.3). Two main functions are responsible for the execution of the Monte-Carlo simulation: **`MC_modelPf.m`** (for a calendar-based simulation) or **`MC_modelPfclock.m`** (for a clock-based simulation). For the calculation of the spacecraft time-to-delivery as described in section 6.2, three functions are used to compute the duration of each of the three main schedule phases (namely, **`InstTtoIdel.m`** for the Instruments Development, **`SC_IandT.m`** for the spacecraft Integration & Testing, and **`SC_shipping.m`** for the spacecraft Shipping). It is in those three functions that historical data is entered to estimate the duration of each schedule phase. The resulting output is the spacecraft time-to-delivery $TD_{s/c}$.

The operations module (as described in section 6.3) is then implemented via two main functions, **`Obsoltimes.m`** to calculate the transition times to obsolescence states for each instrument, and **`Ftimes.m`** to calculate the transition times to failure state for each instrument. The utility profiles $u_j(t)$ delivered by each instrument are then constructed based on all the random obsolescence and failure times, and are finally aggregated to form the utility profile delivered by the spacecraft $u_{SC}(t)$.

The repetition of the process n_{cases} times constitutes the Monte-Carlo simulation that produces distributions for the spacecraft time-to-delivery and total cumulative utility delivered, from which various output metrics can be computed.

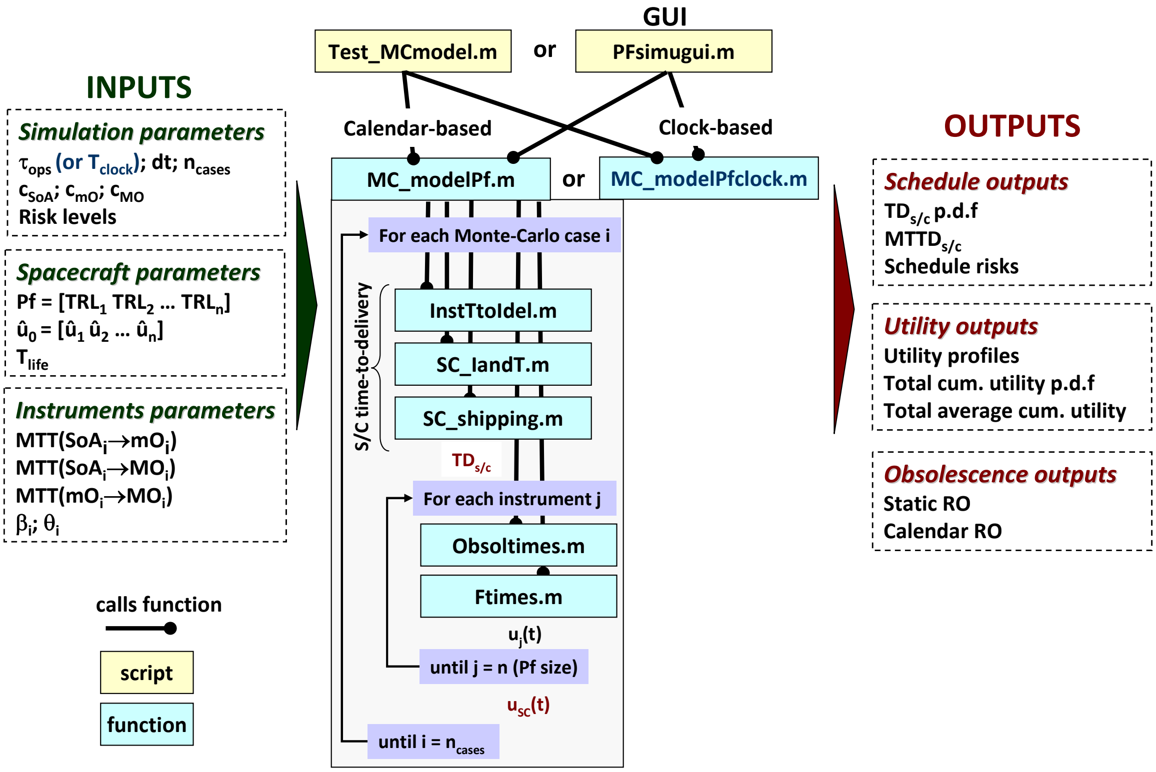


Figure 86. Basic simulation using the integrated framework for a given portfolio configuration (using command or GUI)

Basic simulation for a series of spacecraft based on given portfolio

Figure 87 represents the structure of a basic simulation for a series of spacecraft designed around a given portfolio configuration, following the replacement strategy discussed in section 6.4.2. The instant of development start (or ATP) of spacecraft of generation k t^*_k is calculated according to Eq. 6.11.

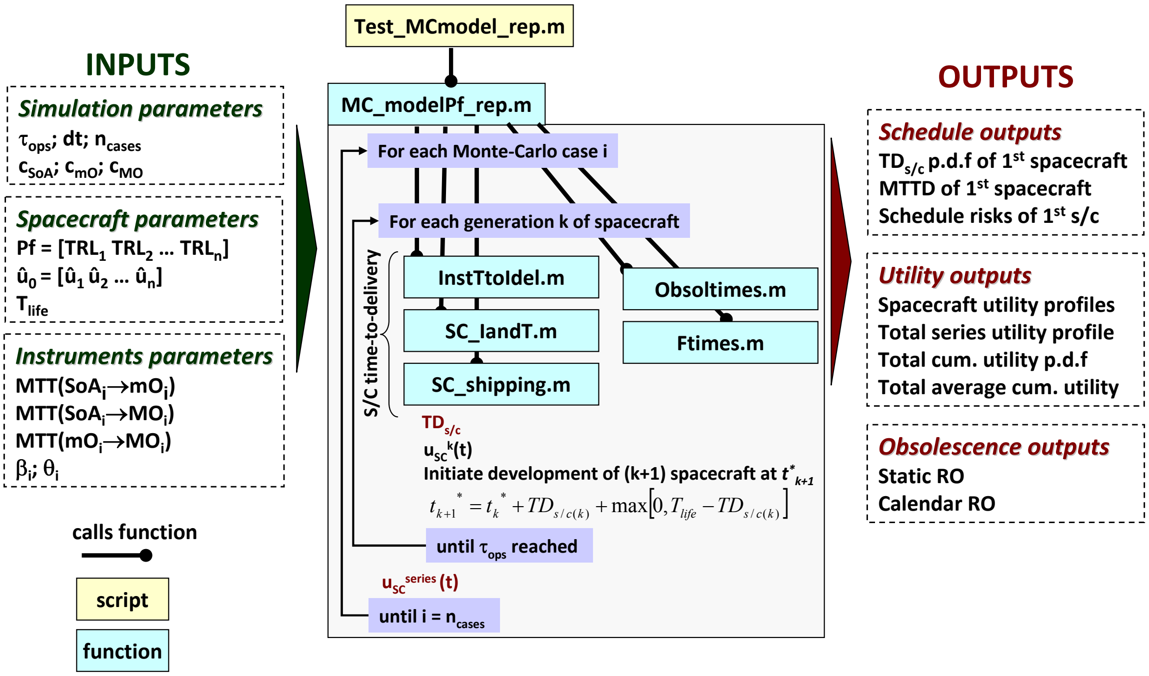


Figure 87. Basic simulation using the integrated framework for a series of spacecraft based on a given portfolio configuration

Impact of TRL and portfolio size on spacecraft time-to-delivery (homogeneous TRL cases)

Figure 88 illustrates the basic algorithm used to investigate the impact of TRL and portfolio size on spacecraft time-to-delivery, for homogeneous TRL cases (as discussed in section 3.5.1). For each value of the common TRL and the number of instruments, the function `MC_modelPf.m` is called to perform the Monte-Carlo simulation and to produce the distribution of the spacecraft time-to-delivery $TD_{s/c}$. When all values of the common TRL and portfolio size have been treated, plots that show the joint impact of portfolio characteristics (TRL and number of instruments) on MTTD and schedule risk can be generated (such as Figure 23 and Figure 24).

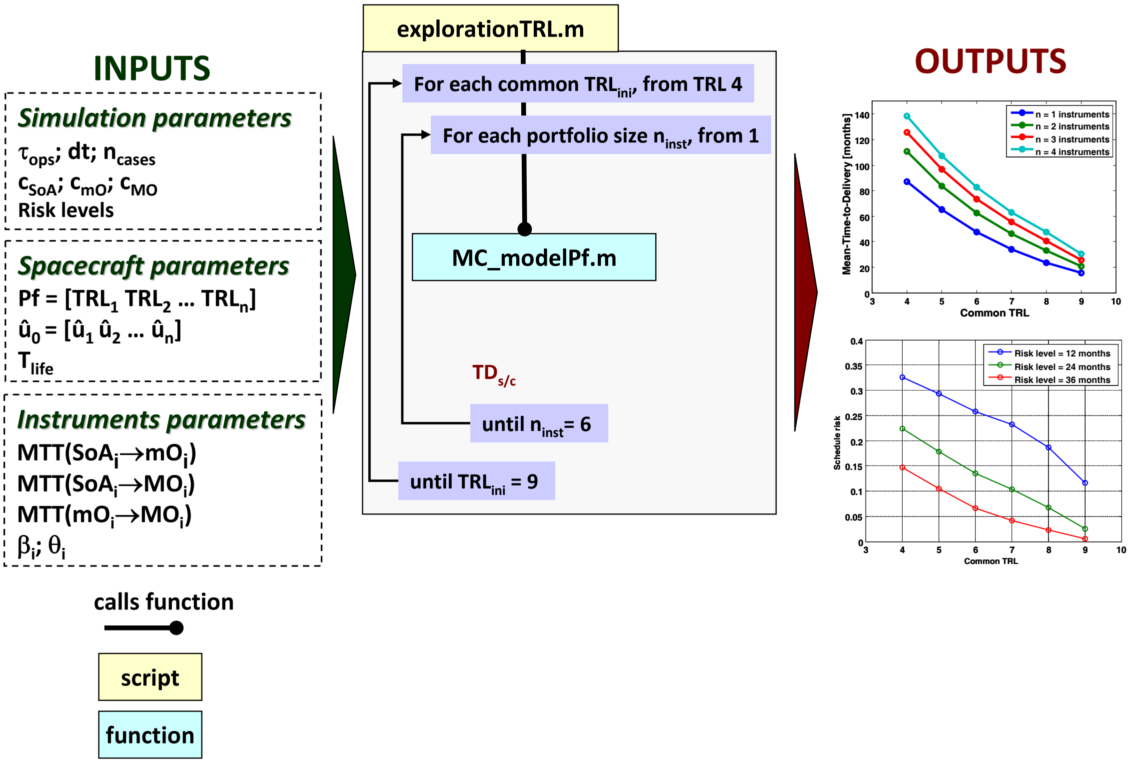


Figure 88. Algorithm used to investigate the impact of common TRL and portfolio size on spacecraft time-to-delivery (illustrative)

Impact of the degree of TRL-heterogeneity on MTTD

Figure 89 illustrates the basic algorithm used to investigate the impact of the degree of TRL-heterogeneity on the MTTD (as discussed in section 3.5.2). For each value of the average portfolio TRL μ_{TRL} and the number of instruments n_{inst}, a set of possible portfolios is constituted and the degree of TRL-heterogeneity δ for each possible portfolio is calculated. For each possible portfolio, the function `MC_modelPf.m` is then called to perform the Monte-Carlo simulation and produce the distribution of the spacecraft time-to-delivery $TD_{s/c}$. When all portfolio combinations with a mean TRL

μ_{TRL} and a number of instruments n_{inst} have been evaluated, plots that show the impact of the degree of TRL-heterogeneity on MTTD can be generated for the values of μ_{TRL} and n_{inst} considered (such as Figure 26).

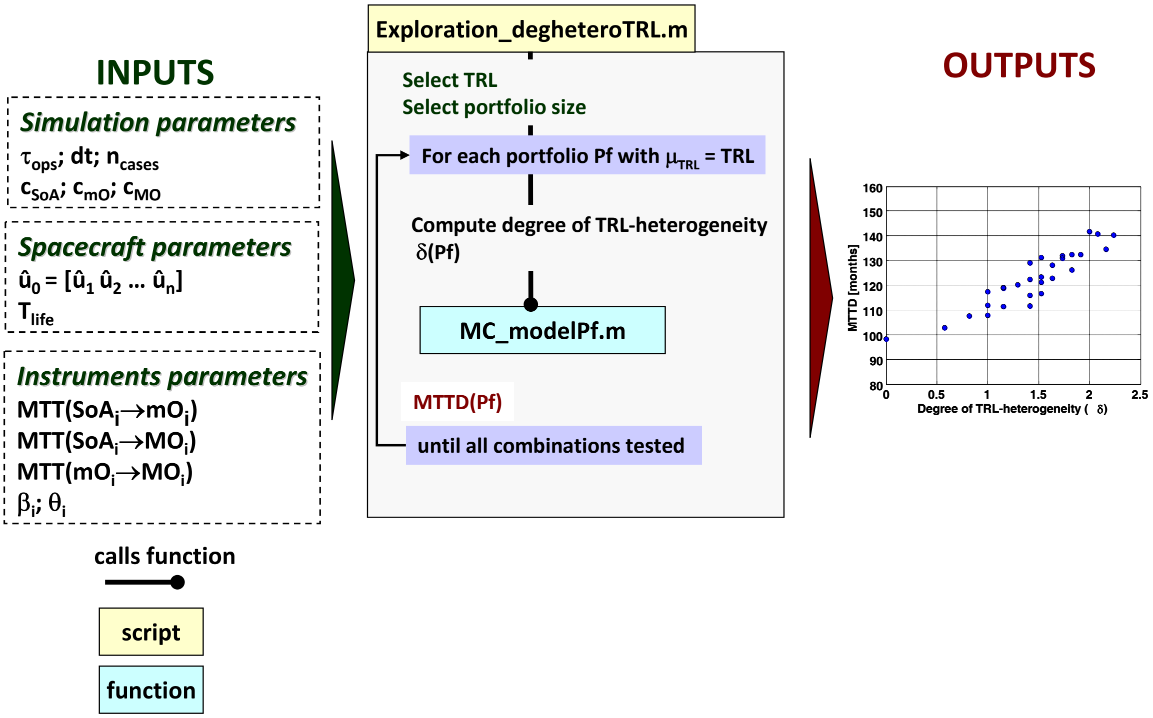


Figure 89. Algorithm used to investigate the impact of TRL heterogeneity on MTTD (illustrative)

Identification of optimal portfolios in calendar-based vs. clock-based optimization mindset

Figure 90 illustrates the basic algorithm used to identify the optimal portfolios depending on the time horizon τ_{ops} considered (in a calendar-based optimization mindset) or the number of years after launch T_{clock} (in a clock-based optimization mindset), as discussed in section 3.6. For example, in the homogeneous TRL case, a value of the common TRL is first selected. For each value of the time-horizon τ_{ops} and the number of instruments

n_{inst}, the cumulative utility delivered over time by each spacecraft portfolio (i.e., for each portfolio size) is evaluated by the function **`MC_modelPf.m`** (in the calendar-based optimization mindset) or the function **`MC_modelPfclock.m`** (in the clock-based optimization mindset). Plots that represent the average cumulative utility delivered by the spacecraft for each portfolio size can then be generated (such as Figure 30), to identify the optimal portfolio size (on a utility basis) depending on the design optimization mindset adopted.

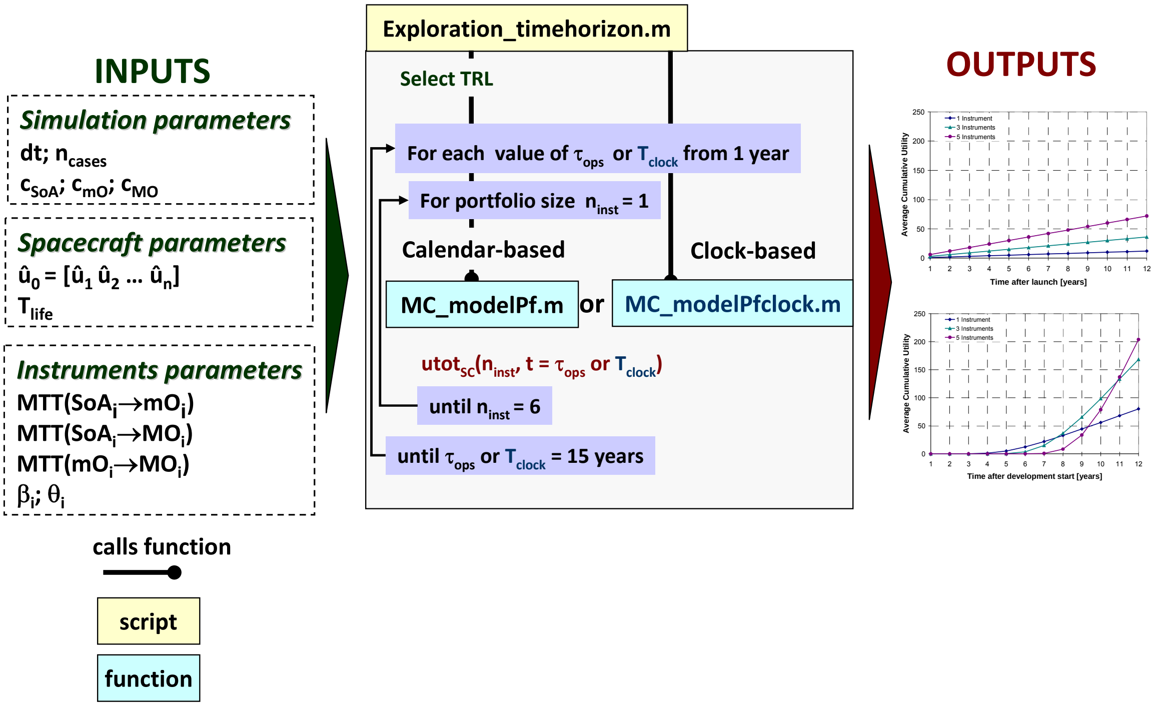


Figure 90. Influence of the time horizon on the optimal portfolios (on a utility basis)

Visualization of all portfolios

For a given value of the time horizon τ_{ops} or time after launch T_{clock}, Figure 91 illustrates the basic algorithm used to evaluate all portfolios combinations, their associated MTTD, schedule risk and cumulative utility. For each value of the portfolio size n_{inst}, all portfolio combinations are first generated. For each portfolio configuration, the distributions of spacecraft time-to-delivery and the cumulative utility over a period of time are then generated via a call of the function **`MC_modelPf.m`** (in the calendar-based optimization mindset) or the function **`MC_modelPfclock.m`** (in the clock-based optimization mindset). The MTTD, schedule risk and average cumulative utility can then be computed. The results can finally be visualized on plots that show all spacecraft portfolio configurations, their MTTD or schedule risk against the average cumulative utility delivered after the period of time considered (such as Figure 32 and Figure 74).

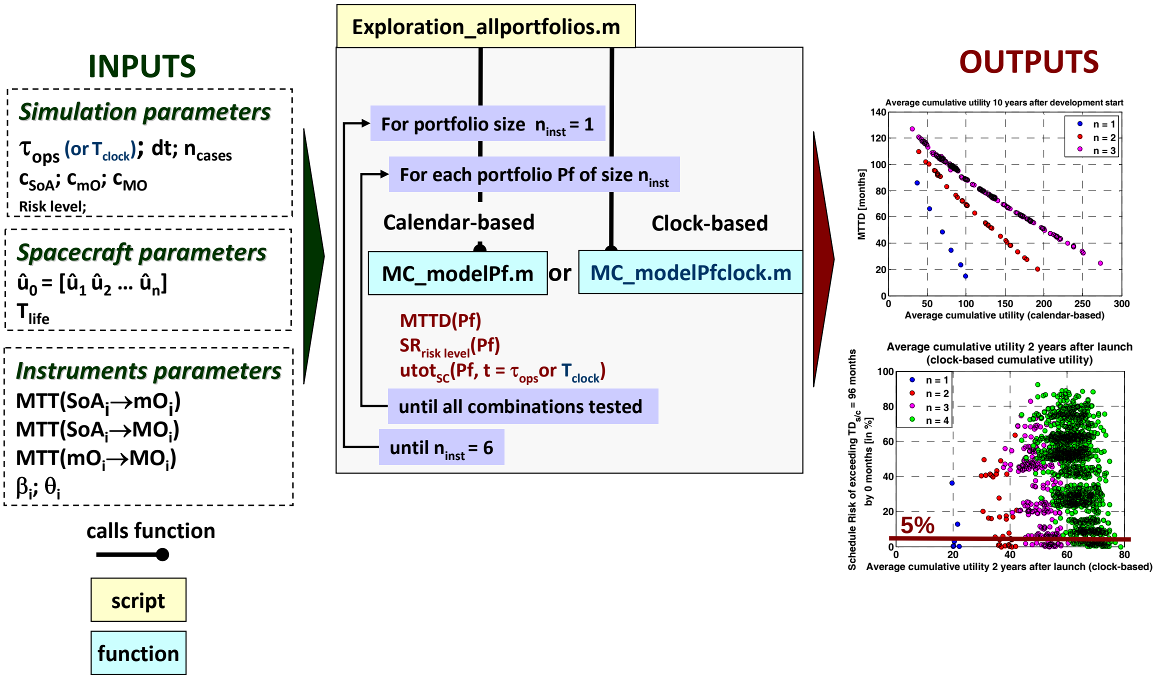


Figure 91. Visualization of all portfolios and their associated MTTD, schedule risk and cumulative utility (clock- or calendar-based)

REFERENCES

[1] Government Accountability Office, Defense Acquisitions: Space System Acquisition Risks and Keys to Addressing Them, GAO-06-776R, June 2006.

[2] Government Accountability Office, Defense Acquisitions: Assessments of Selected Weapon Programs, GAO-07-406SP, Mar. 2007. URL: http://www.gao.gov/docsearch/repandtest.html [accessed 26 July 2007].

[3] Chaplain, C. T., Space Acquisitions: Actions Needed to Expand and Sustain Use of Best Practices, GAO-07-730T, 19 Apr. 2007. URL: http://www.gao.gov/docsearch/repandtest.html [accessed 23 May 2007].

[4] Government Accountability Office, NASA: Assessments of Selected Large-Scale Projects, GAO-09-306SP, March 2009.

[5] Government Accountability Office, NASA Program Costs: Space Missions Require Substantially More Funding Than Initially Estimated, GAO Report No. GAO/NSIAD-93-97, December 1992.
URL: http://archive.gao.gov/d36t11/148471.pdf [accessed 27 February 2011]

[6] Young Panel Report, Report of the Defense Science Board/Air Force Scientific Advisory Board Joint Task Force on Acquisition of National Security Space Programs, May 2003, (updated July 2004).

[7] Government Accountability Office, Military Space Operations: Common Problems and Their Effects on Satellite and Related Acquisitions, GAO Report No. GAO-03-825R, June 2003. URL: http://www.gao.gov/new.items/d03825r.pdf [accessed 27 February 2011].

[8] Department of Defense, Plan for Operationally Responsive Space, A Report to Congressional Defense Committees, April 17, 2007.

[9] Webb J.J. Jr, On-Demand Science Missions, AIAA Paper No. RS3-2005-1003, *AIAA 3rd Responsive Space Conference*, Los Angeles, CA, 25–28 April, 2005.

[10] Shotwell G. and Chinnery A., Space Exploration Technologies' Falcon I Launcher: Towards Operationally Responsive Spacelift, AIAA Paper No. 2004-3905, *40th Joint Propulsion Conference*, Fort Lauderdale, FL, 11-14 July, 2004.

[11] Schoneman S., Amorosi L., Willey R. and Laidley M., OSP-2 Minotaur Family of Space Launch Vehicles for NearTerm, Low Risk Responsive Spacelift, AIAA Paper No. 2005-6620, *AIAA Space 2005 Conference and Exhibit*, Long Beach, CA, August 30 – September 1, 2005.

[12] Williams G., Macklin F., Sarigul-Klijn M., Sarigul-Klijn N. and Benson J., Almost There: Responsive Space, AIAA Paper No. RS2-2004-8000, *AIAA 2nd Responsive Space Conference*, Los Angeles, CA, April 19–22, 2004.

[13] Holweg M. and Pil F.K., Successful Build-To-Order Strategies Start With the Customer, *MIT Sloan Management Review* Vol. 43, No. 1, pp. 74–83, 2001.

[14] Wertz J.R., Responsive Launch Vehicle Cost Model, AIAA Paper No. RS2-2004-2004, *AIAA 2nd Responsive Space Conference*, Los Angeles, CA, April 19–22, 2004.

[15] Brown O. and Eremenko P., Fractionated Space Architectures: A Vision for Responsive Space, AIAA Paper No. RS4-2006-1002, *AIAA 4th Responsive Space Conference*, Los Angeles, CA, 24-27 April 2006.

[16] Guidi C and Skelly D. Transformational Spaceport and Range Technologies, AIAA Paper No. RS2-2004-4002. In AIAA 2nd Responsive Space Conference, Los Angeles, CA, April 19–22, 2004.

[17] McCleskey C.M., Guidi C. and Brown K., Potential Strategies for Spaceport Systems Towards Airport-like Operations, AIAA Paper No. RS2-2004-6003, *AIAA 2nd Responsive Space Conference*, Los Angeles, CA, April 19–22, 2004.

[18] Finger G.W. and Gulliver B.S., Design of Operationally Responsive Launch Sites, AIAA Paper No. 2009-657-645, *47th AIAA Aerospace Sciences Meeting Including The New Horizons Forum and Aerospace Exposition*, Orlando, FL, 5 – 8 January, 2009.

[19] Doyne T., Wegner P., Olmedo C., Moretti G., Hurley M., Johnson M., Duffey T., and Huffine C., ORS and TacSAT Activities Including the Emerging ORS Enterprise, AIAA Paper No. RS5-2007-4001, *AIAA 5th Responsive Space Conference*, Los Angeles, CA, April 23–26, 2007.

[20] Bitten R. E., Bearden D. A., Lao N. Y. and Park T. H., The Effect of Schedule Constraints on the Success of Planetary Missions, *Acta Astronautica*, Vol. 59, pp. 1101–1109, 2006.

[21] Zirger B.J., and Hartley J.L, The Effect of Acceleration Techniques on Product Development Time, *IEEE Transactions on Engineering Management*, Vol. 43, No. 2, pp. 143–152, 1996.

[22] Government Accountability Office. Defense Acquisitions: Improvements Needed in Space Systems Acquisition Management Policy, GAO Report No. GAO-03-1073, September 2003. URL: http://www.gao.gov/new.items/d031073.pdf [accessed 6 October 2009].

[23] Government Accountability Office. Technology Development: New DOD Space Science and Technology Strategy Provides Basis for Optimizing Investments, but Future Versions Need to be More Robust, GAO

Report No. GAO-05-155, January 2005. URL: http://www.gao.gov/new.items/d05155.pdf [accessed 6 October 2009].

[24] Government Accountability Office. Defense Acquisitions: Incentives and Pressures that Drive Problems Affecting Satellite and Related Acquisitions, GAO Report No. GAO-05-570R, June 2005. URL: http://www.gao.gov/new.items/d05570r.pdf [accessed 6 October 2009].

[25] Government Accountability Office. Best Practices: Better Management of Technology Development Can Improve Weapon Systems Outcome, GAO Report No. GAO/NSIAD-99-162, July 1999. URL: http://www.gao.gov/archive/1999/ns99162.pdf [accessed 6 October 2009].

[26] Government Accountability Office. Export Controls: State and Commerce Department License Review Times Are Similar, GAO Report No. GAO-01-528, June 2001. URL: http://www.gao.gov/new.items/d01528.pdf [accessed 30 December 2009].

[27] Government Accountability Office. Defense Trade: State Department Needs to Conduct Assessments to Identify and Address Inefficiencies and Challenges in the Arms Export Process, GAO Report No. GAO-08-89, November 2007. URL: http://www.gao.gov/new.items/d0889.pdf [accessed 30 December 2009].

[28] Air Force Research Laboratory. Defense Industrial Base Assessment: U.S. Space Industry, Final Report. Report No. ADA486673, August 31, 2007. URL: http://handle.dtic.mil/100.2/ADA486673 [accessed 30 December 2009].

[29] Choi E. and Niculescu S., The impact of US export controls on the Canadian space industry, *Space Policy*, Vol. 22, pp. 29–34, 2006.

[30] Booz Allen Hamilton. Moving Toward a Faster and More Predictable Process of Licensing Defense Articles and Services for Export, 2006. URL: http://www.boozallen.com/media/file/Export_Controls_Survey.pdf [accessed 30 December 2009].

[31] Gershenson J. K., Prasad G. J., and Zhang Y. Product Modularity: Definitions and Benefits, *Journal of Engineering Design*, Vol. 14, No. 3, pp. 295–313, 2003.

[32] Ulrich K., and Tung K., Fundamentals of Product Modularity, *Proceedings of the 1991 ASME Design Engineering Technical Conferences - Conference on Design/Manufacture Integration*. Miami, FL. September 22–25, 1991.

[33] Allen K. R. and Carlson-Skalak S., Defining Product Architecture During Conceptual Design., *Proceedings of the 1998 ASME Design Engineering Technical Conference*, Atlanta, GA, 13–16 September, 1998.

[34] Enright J., Jilla C., and Miller D., Modularity and Spacecraft Cost, *Journal of Reducing Space Mission Cost*, Vol 1., No .2, pp. 133–158, 1998.

[35] Lyke J., Fronterhouse D., Cannon S., Lanza D., and Wheaton B., Space Plug-and-Play Avionics, AIAA Paper No. RS3-2005-5001, *AIAA 3rd Responsive Space Conference,* Los Angeles, CA, 25–28 April, 2005.

[36] Fronterhouse D., Lyke J. and Achramowicz S., Plug-and-play Satellite (PnPSat), AIAA Paper No. 2007-2914, *AIAA Infotech@Aerospace 2007 Conference and Exhibit*, Rohnert Park, CA, 7 – 10 May, 2007.

[37] Westley D.M., Grau J., Jordan L. and McDermott S., Modular Spacecraft Standards: Supporting Low-Cost, Responsive Space, AIAA Paper No. 2004-6098, *AIAA Space 2004 Conference and Exhibit*, San Diego, CA, 28 – 30 September, 2004.

[38] Erkorkmaz C., Nimelman M. and Ogilvie A., Spacecraft Payload Modularization for Operationally Responsive space, AIAA Paper RS6-2008-6001, *AIAA 6th Responsive Space Conference*, Los Angeles, CA, April 28–May 1, 2008.

[39] Gell-Mann M., What is Complexity? *Complexity*, Vol. 1. No. 1, pp. 16–19, 1995.

[40] Lloyd S., Measures of complexity: a non-exhaustive list., *IEEE Control Systems Magazine*, Vol. 21, No. 4, pp. 7–8, 2001.

[41] Summers J.D. and Shah J.J., Developing Measures of Complexity for Engineering Design, Paper No. DETC2003/DTM–48633, *Proceedings of DETC'03, ASME 2003 Design Engineering Technical Conference*, Chicago, IL, 2–6 September, 2003.

[42] Braha D. and Maimon O., The Measurement of a Design Structural and Functional Complexity, IEEE *Transactions on Systems, Man, and Cybernetics Part A*, Vol. 28, No. 4, pp. 527–535, 1998.

[43] Bashir H.A. and Thomson V., Models for Estimating Design Effort and Time, *Design Studies*, Vol. 22., No. 2, pp. 141–155, 2001.

[44] Bearden D.A., A Complexity-based Risk Assessment of Low-cost Planetary Missions: When is a Mission Too Fast and Too Cheap? *Acta Astronautica* Vol. 52, No. 3, pp. 371–379, 2003.

[45] Wright T.P., Factors Affecting the Cost of Airplanes., *Journal of Aeronautical Sciences*, Vol. 2, pp. 49–73, 1936.

[46] Boothryd G., Dewhurst P., and Knight W., Product Design for Manufacture and Assembly, 2nd ed., Marcel Dekker Inc.: New York, 2002.

[47] Apgar H. and Bearden D., Cost Modeling. In Space Mission Analysis and Design, 3rd ed., Wertz R and Larson W (eds). Microcosm Press: Torrence, CA, 1999; p. 809.

[48] Sadin S. R., Povinelli F. P., and Rosen R., The NASA Technology Push towards Future Space Mission Systems, *Acta Astronautica*, Vol. 20, pp. 73–77, 1989.

[49] Mankins JC, Technology Readiness Levels, White Paper. NASA Office of Space Access and Technology, 1995. URL: www.hq.nasa.gov/office/codeq/trl/trl.pdf [accessed 6 October 2009].

[50] Browning, T. R., Sources of Schedule Risk in Complex System Development, *Systems Engineering*, Vol. 2, No. 3, 1998, pp. 129-142.

[51] Gupta, A. and Wilemon, D., Accelerating the development of technology-based new products, *California Management Review*, Vol. 32, No.2, Winter 1990, pp. 24-44.

[52] Government Accountability Office, NASA: Implementing a Knowledge-Based Acquisition Framework Could Lead to Better Investment Decisions and Projects Outcomes, GAO-06-218, Dec. 2005, pp. 15-16. URL: http://www.gao.gov/new.items/d06218.pdf [accessed 26 December 2007].

[53] Government Accountability Office, Defense Acquisitions: Assessments of Selected Major Weapon Programs, GAO-05-301, March 2005, pp. 10-11. URL: http://www.gao.gov/new.items/d05301.pdf [accessed 26 December 2007].

[54] George, T., Powers, R., Closing the TRL gap, *Aerospace America*, August 2003, pp 24-26.

[55] Lee, T., Thomas, L. D., Cost Growth Models for NASA's Programs, *Journal of Probability and Statistical Science*, Vol. 1, 2003, pp. 265-279.

[56] Smith J., An Alternative to Technology Readiness Levels for Non-Developmental Item (NDI) Software, Carnegie Mellon, CMU/SEI-2004-TR-013, ESC-TR-2004-013, Pittsburgh, PA, April 2004.

[57] Sauser B., Ramirez-Marquez J., Magnaye R., and Tan W., A Systems approach to expanding the technology readiness level within defense acquisition, *Int. J. Defense Acquisition Manage.*, Vol 1., pp 39–58, 2008.

[58] Ramirez-Marquez J. E., and Sauser B. J., System Development Planning via System Maturity Optimization, *IEEE Transactions on Engineering Management*, Vol. 56, No. 3, August 2009.

[59] Sauser B., Gove R., Forbes E. and Ramirez-Marquez J. E., Integration maturity metrics: Development of an integration readiness level, *Information Knowledge Systems Management*, Vol. 9, pp. 17–46, 2010.

[60] Mankins J.C., Approaches to Strategic Research and technology (R&T) Analysis and Road Mapping, *Acta Astronautica*, Vol. 51, pp. 3–21, 2002.

[61] Sauser B., Verma D., Ramirez-Marquez J., and Gove R., From TRL to SRL : the Concept of System Readiness Levels, *Conference on Systems Engineering Research (CSER)*, Los Angeles, CA, USA, 2006.

[62] Government Accountability Office, Defense Acquisitions: Despite Restructuring, SBIRS High Program Remains at Risk of Cost and Schedule Overruns, GAO-04-48, Oct. 2003, p. 3.

[63] Markowitz H., Portfolio Selection, *The Journal of Finance*, Vol. 7, pp. 77–91, 1952.

[64] Griffin A., PDMA Research on New Product Development Practices: Updating Trends and Benchmarking Best Practices, *Journal of Product Innovation Management*, Vol. 14, pp. 429–458, 1997.

[65] Loch, C. H., and Kavadias, S., Handbook of New Product Development Management, Butterworth-Heinemann, Oxford, UK, 2008.

[66] Roussel, P. A., Saad, K. N., and Erickson, T. J., Third Generation R&D: Managing the Link to Corporate Strategy, Harvard Business School Press, Boston, MA, 1991.

[67] Cooper R. G., Edgett. S. J., and Kleinschmidt E. J., New Product Portfolio Management: Practices and Performance, *Journal of Product Innovation Management*, Vol. 16, pp. 333–351, 1999.

[68] Archer N.P., and Ghasemzadeh, F., An integrated framework for project portfolio selection, *International Journal of Project Management*, Vol.17, No. 4, pp. 207–216, 1999.

[69] Schniederjans M. J., and Santhanam R., A multi-objective constrained resource information system project selection method, *European Journal of Operational Research*, Vol. 70, pp. 244–253, 1993.

[70] Government Accountability Office, Best Practices: An Integrated Portfolio Management Approach to Weapon System Investments Could Improve DOD's Acquisition Outcomes, GAO-07-388, Mar. 2007.

[71] Cooper R. G., Edgett S. J., and Kleinschmidt E. J., Portfolio Management For New Products, 2nd edition, Perseus Books, Cambridge, MA, 2001.

[72] Kaplan R. S., and Norton D. P., Having Trouble with Your Strategy? Then Map It, *Harvard Business Review*, Sept.–Oct. 2000, pp. 167–176.

[73] Baker N., and Freeland J., Recent advances in R&D Benefit Measurement and Project Selection Methods, *Management Science*, Vol. 21, No. 10, June 1975.

[74] Chien C-F., A portfolio-evaluation framework for selecting R&D projects, *R&D Management*, Vol.32, No. 4, 2002.

[75] Linton J. D., Walsh S. T., and Morabito J., Analysis, ranking and selection of R&D projects in a portfolio, *R&D Management*, Vol. 32, No. 2, 2002.

[76] Henriksen A. D., and Taynor A. H., A Practical R&D Project-Selection Scoring Tool, *IEEE Transactions on Engineering Management*, Vol. 46, No. 2, May 1999.

[77] Martino J. P., Research and Development Project Selection, Wiley-Interscience, New York, NY, 1995.

[78] Chun Y. H., Sequential Decisions Under Uncertainty in the R&D Project Selection Problem, *IEEE Transactions on Engineering Management*, Vol. 41, No. 4, November 1994.

[79] Hess S. W., Swinging on the Branch of a Tree: Project Selection Applications, *Interfaces*, Vol.23, No. 6, pp. 5–12, Nov.–Dec. 1993,

[80] Faulkner T. W., Applying Options Thinking to R&D Valuation, *Research Technology Management*, Vol. 39, No. 3, pp. 50–56, May–June 1996.

[81] Rouse W. B., and Boff K. R., Value-centered R&D organizations: Ten principles for characterizing, assessing, and managing value, *Systems Engineering*, Vol.7, No. 2, pp. 167–185, June 2004.

[82] Bodner D. A., and Rouse, W. B., "Understanding R&D value creation with organizational simulation," Systems Engineering, Vol. 10, No. 1, January 2007, pp. 64–82.

[83] Hall, D. L., and Nauda, A., An Interactive Approach for Selecting IR&D Projects, *IEEE Transactions on Engineering Management*, Vol. 37, No. 2, May 1990.

[84] Zahedi F., The analytic hierarchy process – A survey of the method and its applications, *Interfaces*, Vol. 16, No. 4, pp. 96–108, Jul.–Aug. 1986.

[85] Lockett G., Hetherington B., Yallup P., Stratford M., and Cox B., Modeling a research portfolio using AHP: A group decision process, *R&D Management*, Vol. 16, No. 2, 1986.

[86] Souder W. E., Analytical Effectiveness of Mathematical Models for R&D Project Selection, *Management Science*, Vol.19, No. 8, April 1973.

[87] Golabi K., Kirkwood C. W., and Sicherman A., Selecting a Portfolio of Solar Energy Projects using Multiattribute Preference Theory, *Management Science*, Vol. 27, No.2, February 1981.

[88] Saleh J. H., Perspectives in Design: the deacon's masterpiece and the hundred-year aircraft, spacecraft, and other complex engineering systems, *Journal of Mechanical Design*, Vol. 127, pp. 845–850, September 2005.

[89] NASA Systems Engineering Handbook, SP-6105, June 1995.

[90] Mun J., Modeling Risk: Applying Monte Carlo Simulation, Real Options Analysis, Forecasting, and Optimization Techniques, Wiley, Hoboken, NJ, 2006.

[91] Kaplan S., and Garrick B. J., On the quantitative definition of risk, *Risk analysis*, Vol. 1, No. 1, pp. 11–27, 1981.

[92] Farquhar P. H., and Rao V. R., A Balance Model for Evaluating Subsets of Multiattributed Items, *Management Science*, Vol. 22, No. 5, January 1976.

[93] Brathwaite J., and Saleh J. H., Value-Centric Framework and Pareto Optimality for Design and Acquisition of Communication Satellites, *International Journal of Satellite Communications and Networking*, Vol. 27, No. 6, pp. 330-348, 2009.

[94] Brathwaite J., and Saleh J. H., On the concept of value, its quantification, and importance in space systems design and acquisition, *AIAA SPACE 2008 Conference and Exposition*, San Diego, California, Sep. 9-11, 2008.

[95] Doggrell L., Operationally Responsive Space: A Vision for the Future of Military Space, *Air & Space Power Journal*, Vol. 20, No. 2, pp. 42–49, 2006, AFRP 10-1.

[96] Naylor L. L., Culture and Change, An Introduction, Bergin Garvey/Greenwood, Westport, CT, 1996.

[97] Singh P., and Sandborn P., Obsolescence Driven Design Refresh Planning for Sustainment-Dominated Systems, *The Engineering Economist*, Vol. 51, pp. 115–139, 2006.

[98] Li A, Use of Cost Reduction Plans in Estimating F-22 Total Production Costs. Government Accountability Office Report, GAO/T-NSIAD-00-200, 2000.

[99] Pickett J. H., The American Heritage Dictionary of the English Language, Fourth Edition. Houghton Mifflin Company, Boston, MA, 2000.

[100] Levinthal D. A. and Purohit D., Durable Goods and Product Obsolescence, *Marketing Science*, Vol. 8, pp. 35-56, 1989.

[101] Egghe L. and Rousseau R., Aging, Obsolescence, Impact, Growth, and Utilization: Definitions and Relations, *Journal of the American Society for Information Science*, Vol. 51, pp. 1004-1017, 2000.

[102] Fitzhugh G., Rapid Retargeting: A Solution To Electronic Systems Obsolescence. *Proceedings of the IEEE National Aerospace and Electronic Conference*, NAECON, pp. 169–176, 1998.

[103] Tomczykowski W., Fritz A., and Scalia R., Program Managers Handbook: Common Practices to Mitigate the Risk of Obsolescence. Prepared for the Defense Micro-Electronics Activity (DMEA), McClean Air Force Base, ARINC, 2000.

[104] Sorensen J. B., and Stuart T. E., Aging, Obsolescence and Organizational Innovation, *Administrative Science Quaterly*, Vol. 45, pp. 81 – 112, 2008.

[105] Song J. S. and Zipkin P. H., Managing Inventory with the Prospect of Obsolescence, *Operational Research*, Vol. 44, pp. 215 – 24, 1993.

[106] Borgonovo E., Marseguerra M., and Zio E., A Monte Carlo Methodological Approach to Plant Availability Modeling with Maintenance, Aging, and Obsolescence, *Reliability Engineering and System Safety*, Vol. 67, pp. 61–73, 2000.

[107] Tan Z., Telecommunications, Technology, and China's Modernization. *Proceedings of the Conference of China's Emerging Technological Trajectory in the 21st Century*, Rensselaer Polytechnic Institute, Troy, New York, September 4-6, 2003.

[108] Clavareau J. and Labeau P.-E., A Petri net-based modelling of replacement strategies under technological obsolescence, *Reliability Engineering and System Safety*, Vol. 94, pp. 357 – 369, 2009.

[109] Cooper T., Inadequate Life? Evidence of Consumer Attitudes to Product Obsolescence, *Journal of Consumer Policy*, Vol. 27, pp. 421 – 449, 2004.

[110] Nordhaus W. D., Do Real-Output and Real-Wage Measures Capture Reality? The History of Lighting Suggests Not. Cowles Foundation Paper No. 957, Cowles Foundation for Research in Economics at Yale University, 1998.

[111] Defense Science Board, Office of the Undersecretary of Defense for Research and Engineering, 1981 Summer Study Panel on Operational Readiness with High Performance Systems. ADA Report 120223, Washington DC, April 1982.

[112] Hargadon A. B. and Douglas Y., When Innovations Meet Institutions: Edison and the Design of the Electric Light, *Administrative Science Quaterly*, Vol. 46, pp. 476–501, 2001.

[113] Israel P. B., Nier K. A., and Carlat L., The Papers of Thomas A. Edison: The Wizard of Menlo Park, 1878, Johns Hopkins University Press, Baltimore, MD, 1998.

[114] Katz M. L. and Shapiro C., Network Externalities, Competition, and Compatibility, *The American Economic Review*, Vol. 75, pp. 424–440, 1985.

[115] Gandal N., Compatibility, Standardization, and Network Effects: Some Policy Implications, *Oxford Review of Economic Policy*, Vol. 18, pp. 80–91, 2002.

[116] Liebowitz S. J. and Margolis S. E., Path Dependence, Lock-in, and History, *Journal of Law, Economics and Organization*, Vol. 11, pp. 205–226, 1995.

[117] Arthur W. B., Competing Technologies Increasing Returns, and Lock-In by Historical Events, *The Economic Journal*, Vol. 99, pp. 116–131, 1989.

[118] David P. A., Clio and the Economics of QWERTY, *Economic History*, Vol. 75, pp. 332–337, 1985.

[119] Sandborn P. and Myers J., Designing Engineering Systems for Sustainability in Handbook of Performability Engineering, Misra, K.B. (ed), Springer, London, UK, pp. 81–103, 2008.

[120] Mansfield E., Technical Change and the Rate of Imitation, *Econometrica*, Vol. 29, No.4, pp. 741–766., Oct. 1961.

[121] Bass F. M., A New Product Growth for Model Consumer Durables, *Management Science*, Vol. 15, pp. 215-227, 1969.

[122] Mahajan V., Muller E., and Bass F. M., New Product Diffusion Models in Marketing: A Review and Directions for Research, *Journal of Marketing*, Vol. 54, pp. 1–26, 1990.

[123] Fisher J. C. and Pry R. H., A Simple Substitution Model of Technological Change, *Technological Forecasting and Social Change*, Vol. 3, pp. 75-88, 1971.

[124] Norton J. A. and Bass F. M., A Diffusion Theory Model of Adoption and Substitution for Successive Generations of High-Technology Products, *Management Science*, Vol. 33, pp. 1069–1086, 1987.

[125] Maier F.H., New product diffusion models in innovation management – a system dynamics perspective, *System Dynamics Review*, Vol. 14, pp. 285–308, 1998.

[126] Milling P. M., Modeling innovation processes for decision support and management simulation, *Systems Dynamics Review*, Vol. 12, pp. 211–234, 1996.

[127] Lemer A. C., Infrastructure Obsolescence and Design Service Life, *Journal of Infrastructure Systems*, Vol. 2, pp. 153–161, 1996.

[128] U.S. Federal Communications Commission, Public Mobile Services, 47 CFR Part 22, Code of Federal Regulations, 2009.
URL: http://www.gpo.gov/fdsys/pkg/CFR-2009-title47-vol2/pdf/CFR-2009-title47-vol2-part22.pdf [accessed 1 October 2010]

[129] U.S. Department of Justice, ADA Standards for Accessible Design, 28 CFR Part 36, Code of Federal Regulations, Revised as of July 1, 1994. URL: http://www.ada.gov/adastd94.pdf [accessed 1 October 2010].

[130] U.S. Environmental Protection Agency, Motor Vehicle Emission and Fuel Standards, Clean Air Act, Title II, Part A, as amended in 1990.
URL: http://www.law.cornell.edu/uscode/html/uscode42/usc_sec_42_00007521----000-.html [accessed 1 October 2010].

[131] European Parliament and Council, Regulation (EC) No 1907/2006 of the European Parliament and of the Council of 18 December 2006 concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH), 2006.
URL: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2006:396:0001:0849:EN:PDF [accessed 1 October 2010].

[132] Brown G.W., Lu J.Y., and Wolfson R.J., Dynamic modeling of inventories subject to obsolescence, *Management Science*, Vol. 11, pp. 51–63, 1964.

[133] Bradley M., and Dawson R. J., An analysis of obsolescence risk in IT systems, *Software Quality Journal*, Vol. 7, pp. 123–130, 1998.

[134] Curtis P., Family Practice History: Bloodletting, *Canadian Family Physician*, Vol. 27, pp. 1030–1032, 1981.

[135] Krugler D. F., This is only a test: How Washington D.C Prepared for Nuclear War, Palgrave MacMillan, New York, NY, 2006.

[136] Rose K. D., One Nation Underground, The Fallout Shelter in American Culture, New York University, New York, NY, 2001.

[137] Steiger J. D., Azcuenaga M. L., Owen D. K., Starek R. B. III, Yao D. A., and Clark D. S., Federal Trade Commission 1994 Annual Report, 1994. URL: http://www.ftc.gov/os/annualreports/ar1994.pdf [accessed 1 October 2010].

[138] Packard V., The Waste Makers, David McKay Company, New York, NY, 1960.

[139] Hotelling H., A General Mathematical Theory of Depreciation, *Journal of the American Statistical Association*, Vol. 20, No. 151, pp. 340–353, Sept. 1925.

[140] Hill P., Foreseen Obsolescence and Depreciation, Manuscript, 1999.
URL: http://www.oecd.org/dataoecd/13/25/2550240.pdf [accessed February 10, 2011]

[141] Katz A. J. and Herman S. W., Improved Estimates of Fixed Reproducible Tangible Wealth, 1929-95. *Survey of Current Business*, Vol. 77, pp. 69–92, 1997.

[142] Hicks J.R., Maintaining capital intact: A further suggestion, *Economica*, Vol. 9, pp. 174–179, 1942.

[143] Fraumeni B. M., The Measurement of Depreciation in the U.S. National Income and Product Accounts, *Survey of Current Business*, Vol. 77, pp. 7-23, 1997.

[144] Hulten C. R., and Wykoff F. C., The Measurement of Economic Depreciation. Depreciation, Inflation, and the Taxation of Income from Capital, Urban Institute Press, Washington D.C, 1980.

[145] BEA Depreciation Rates, Service Lives, and Declining-Balances Rates, available online at:
http://www.bea.gov/scb/account_articles/national/0597niw/tablea.htm [accessed 1 October 2010]

[146] van Delft Ch. and Vial J.P., Discounted costs, obsolescence and planned stockouts with the EOQ formula, *International Journal of Production Economics*, Vol. 44, pp. 255–265, 1996.

[147] Song Y., and Lau H. C., A Periodic Review Inventory Model with Application to the Continuous Review Obsolescence Problem, *European Journal of Operational Research*, Vol. 159, pp. 110–120, 2004.

[148] David I. and Greenshtein E., Brownian Analysis of a Buffered-Flow System in the Face of Sudden Obsolescence, *Operations Research Letters*, Vol. 19, pp. 43–49, 1996.

[149] Masters J. M., A Note on the Effect of Sudden Obsolescence on the Optimal Lot Size, *Decision Sciences*, Vol. 22, No. 5, pp. 1180-1186, 1991.

[150] Joglekar P. and Lee P., An exact formulation of inventory costs and optimal lot sizes in fase of sudden obsolescence, *Operations Research Letters*, Vol. 14, pp. 283–290, 1993.

[151] Cobbaert K. and Van Oudheusden D., Inventory models for fast moving spare parts subject to “sudden death” obsolescence, *International Journal of Production Economics*, Vol. 44, pp. 239–248, 1996.

[152] Saleh J. H., Perspectives in Design: The Deacon's Masterpiece and the Hundred-Year Aircraft, Spacecraft, and Other Complex Engineering Systems, *Journal of Mechanical Design*, Vol. 127, pp. 845–850, 2005.

[153] Rajagopalan S., Capacity Expansion and Equipment Replacement: a Unified Approach, *Operations Research*, Vol. 46, pp. 846–857, 1998.

[154] Pritchard A., Statistical bibliography or bibliometrics? *Journal of Documentation*, Vol. 25, pp. 348–349, 1969.

[155] Gupta B. M., Growth and obsolescence of literature in theoretical population genetics, *Scientometrics*, Vol. 42, pp. 335–347, 1998.

[156] Egghe L., Ravichandra Rao I. K., Citation Age Data and the Obsolescence Function: Fits and Explanations, *Information Processing & Management*, Vol. 28, No. 2, pp. 201–217, 1992.

[157] Brookes B. C., Obsolescence of Special Library Periodicals: Sampling Errors and Utility Contours, *Journal of the American Society for Information Science*, Vol. 21, pp. 320–329, Sept.-Oct. 1970.

[158] Burton R.E. and Kebler R.W., The “half-life” of some scientific and technical literatures, *American Documentation*, Vol. 11, pp. 18–22, 1960.

[159] Gupta U., Obsolescence of physics literature: Exponential decrease of the density of citations to Physical Review articles with age, *Journal of the American Society for Information Science*, Vol. 41, pp. 282–287, 1990.

[160] Solomon R., Sandborn P. A. and Pecht M. G, Electronic Part Life Cycle Concepts and Obsolescence Forecasting, *IEEE Transactions on Components and Packaging Technologies*, Vol. 23, pp. 707–717, 2000.

[161] Sandborn P., Trapped on technology’s trailing edge, *IEEE Spectrum*, Vol. 45, No. 4, pp. 42–58, 2008.

[162] Merola L., The COTS Software Obsolescence Threat, *Proceedings of the International Conference on Commercial-Off-The-Shelf (COTS) Based Software Systems*, 2006.

[163] Sandborn P., Software Obsolescence – Complicating the Part and Technology Obsolescence Management Problem, *IEEE Transactions on Components and Packaging Technologies*, Vol. 30, pp. 886–888, 2007.

[164] Cordero R., Managing for Speed To Avoid Product Obsolescence: A Survey of Techniques, *Journal of Product Innovation*, Vol. 8, pp. 283–292, 1991.

[165] Qualls W., Olshavsky R. W., and Michaels R. E, Shortening of the PLC – An Empirical Test, *Journal of Marketing*, Vol. 45, pp. 76-80, 1981.

[166] Condra L. W., Anissipour A. A., Mayfield D. D., and Pecht M. G., Electronic Components Obsolescence, *IEEE Transactions on Components, Packaging, and Manufacturing Technology–Part A*, Vol. 20, pp. 368–371, 1997.

[167] ANSI/EIA-724 American Standard, Product Life Cycle Data Model, 1997.

[168] Solomon R., Sandborn P. A., and Pecht M. G, Electronic Part Life Cycle Concepts and Obsolescence Forecasting, *IEEE Transactions on Components and Packaging Technologies*, Vol. 23, pp. 707–717, 2000.

[169] Hatch S., Diminishing manufacturing sources and material shortages management practices, *Proceedings of the 2000 Diminishing Manufacturing Sources and Material Shortages (DMSMS) conference*, 2000.

[170] Handfield R. B., and Pannesi R. T., Managing component life cycles in dynamic technological environments, *International Journal of Purchasing and Materials Management*, Vol. 30, pp. 19-27, 1994.

[171] Rink D. R. and Swan J. E., Product Life Cycle Research: A Literature Review, *Journal of Business Research*, Vol. 7, pp. 219-242, 1979.

[172] Precht M. G. and Das D., Editorial – Electronic Part Life Cycle, *IEEE Transactions on Components and Packaging Technologies*, Vol. 23, pp. 190-193, 2000.

[173] Greenstein S. M. and Wade J. B., The product life cycle in the commercial mainframe computer market, 1968–1982, *RAND Journal of Economics*, Vol. 29, pp. 772–789, 1998.

[174] Sandborn P., Prabhakar V., and Ahmad O., Forecasting electronic part procurement lifetimes to enable the management of DMSMS obsolescence, *Microelectronics Reliability*, Vol. 51, pp. 392–399, 2011.

[175] Stogdill R. C., Dealing with obsolete parts, *IEEE Design & Test of Computers*, Vol. 16, pp. 17–25, 1999.

[176] Howard M. A., Component Obsolescence It’s Not Just for Electronics Anymore, *Proceedings of the FAA/DOD/NASA Aging Aircraft Conference*, San Francisco, Ca, 16-19 September 2002.

[177] Wright M. B., Humphrey D. and McCluskey F. P., Uprating Electronic Components for Use Outside Their Temperature Specifications Limits, IEEE *Transactions on Components, Packaging, and Manufacturing Technology – Part A*, Vol. 20, pp. 252–256, 1997.

[178] Sandborn P., Beyond reactive thinking—We should be developing proactive approaches to obsolescence management too! *DMSMS Center of Excellence Newsletter*, Vol. 2, pp. 4–9, 2004.

[179] Saleh J.H, Analysis of Marginal Cost of Durability and Cost per Operational Day: A First Step Towards a Rational Choice of Durability, *Journal of Engineering Design*, Vol. 19, No. 1, pp. 55–74, 2008.

[180] Saleh J.H., Flawed metrics*: satellite cost per transponder and cost per day (*for guiding design decisions), *IEEE Transactions on Aerospace and Electronic Systems*, Vol. 44, No. 1, pp. 147–156, 2008.

[181] McHale J., Commercial aircraft avionics leveraged for next-generation NASA spacecraft, *Avionics Intelligence*, [online article], Nov. 2008, URL: http://avi.pennnet.com/display_article/346535/143/NEWS/none/none/1/Cockpit-for-the-stars/ [accessed 10 June, 2009].

[182] Sonnenberg F.A., Beck J.R., Markov Models in Medical Decision Making: A Practical Guide, *Medical Decision Making*, Vol. 13, pp. 322–339, 1993.

[183] Briggs A., Sculpher M., An Introduction to Markov Modeling for Economic Evaluation, *PharmacoEconomics,* Vol. 13, No. 4, pp. 397–409, 1998.

[184] Sahner R., Trivedi K.S., Puliafito A., Performance and reliability analysis of computer systems : an example-based approach using the SHARPE software package, Kluwer Academic Publishers, Norwell, MA, 1996.

[185] Yates R.D., Goodman D.J., Probability and Stochastic Processes: A Friendly Introduction for Electrical and Computer Engineers, 2nd ed., Wiley, Hoboken, NJ, 2005.

[186] Durrett R., Essentials of Stochastic Processes, Springer, New York, 2001.

[187] Bremaud P., Markov Chains, Springer, New York, 1999.

[188] Livingston H., GEB1: Diminishing Manufacturing Sources and Material Shortages (DMSMS) Management Practices, *Proceedings of the DMSMS Conference*, 2000.

[189] Fishman G.S., Monte Carlo: concepts, algorithms, and applications, Springer-Verlag, New York, 1996.

[190] Hogg R.V., Tanis E.A., Probability and statistical inference, Pearson Education, Upper Saddle River, NJ, 2006, pp. 385–394.

[191] Cumming G., Fidler F., Vaux D.L., Error bars in experimental biology, *Journal of Cell Biology*, Vol. 177, No. 1, pp. 7–11, 2007.

[192] Osiander R., Darrin A. G., Champion J., MEMS and Microstructures in aerospace applications, p. 112, 2006, CRC Press, Boca Raton:FL, USA.

[193] McMillan V. C., Technology Transition a Model for Infusion and Commercialization, IAC-06-E5.1.04, *60th International Astronautical Congress*, Valencia, Spain, Oct. 2006.

[194] Braun, R. D., NASA Innovation and Technology Preliminary Planning,
URL: http://www.spacepolicyonline.com/pages/images/stories/Braun_-_NASA_OCT_March_9_ASEB.pdf [accessed March 28, 2011]

[195] Mankins J.C., Approaches to Strategic Research and technology (R&T) Analysis and Road Mapping, *Acta Astronautica*, Vol. 51, pp. 3–21, 2002.

[196] Cornford S. L. and Sarsfield L., Quantitative Methods for Maturing and Infusing Advanced Spacecraft Technology, *2004 IEEE Aerospace Conference Proceedings*, pp 663–681, 2004.

[197] Swain M. R., Deming D., Vasisht G., Henning T., Bouwman J., and Akeson R. THESIS - the Terrestrial and Habitable-zone Exoplanet Spectroscopy Infrared Spacecraft, Astro2010: The Astronomy and Astrophysics Decadal Survey, Technology Development Papers, No. 61, 2009. URL: http://adsabs.harvard.edu/cgi-bin/nph-data_query?bibcode=2009astro2010T..61S&link_type=ARTICLE&db_key=AST&high= [accessed February 7, 2011].

[198] Hopkins R.C., Johnson C.L., Kouveliotou C., Jones D., Baysinger M., Bedsole T., Maples C.D., Benfield P.J., Turner M., Capizzo P., Fabisinski L., Hornsby L., Thompson K., Miernik J.H. and Percy T. Xenia Mission: Spacecraft Design Concept, NASA/TM-2009-216270, December 2009.

[199] Kouveliotou C., Xenia: A Probe of Cosmic Chemical Evolution, Astro2010 Response to Request for Information.
URL: http://www.stsci.edu/~marel/decadal/rfi/xenia_RFI_final.pdf [accessed February 7, 2011].

[200] Bookbinder J., on behalf of the IXO Study Coordination Group, The International X-Ray Observatory, Activity submission in response to the Astro 2010 RFI#2, August 2009.
URL: http://constellation-x.nasa.gov/decadal_references/IXOAstro2010RFI2Web.pdf [accessed February 7, 2011].

[201] Kramer H. H., Observation of the earth and its environment: survey of missions and sensors, 4th edition, Springer, Berlin, Germany, 2002.

[202] Castet J-F. and Saleh J.H., Satellite and satellite subsystems reliability: Statistical data analysis and modeling, *Reliability Engineering and Systems Safety*, Vol. 94, pp. 1718–1728, 2009.

[203] Leemis L. M., Reliability – Probabilistic Models and Statistical Methods, 2^{nd} ed., Leemis, 2009.

[204] Covault C., Advanced KH-11 Broadens U.S. Recon Capability, *Aviation Week and Space Technology*, Vol. 146, No.1, p. 24, 1997.

[205] Covault C., NRO KH-11 Readied For Afghan Recon., *Aviation Week and Space Technology*, Vol. 155, No.15, pp. 68–69, 2005.

[206] Dubos G. F. and MacDonald A., Tracking Cost and Schedule Growth of Unmanned Spacecraft: Lessons Learned from NASA's CADRe Database, IAC-09-D1.5.5, *60th International Astronautical Congress*, Daejeon, Republic of Korea, Oct. 2009.

[207] Azizian N., Sarkani S., and Mazzuchi T., A Comprehensive Review and Analysis of Maturity Assessment Approaches for Improved Decision Support to Achieve Efficient Defense Acquisition, *Proceedings of the World Congress on Engineering and Computer Science 2009*, Vol. 2, WCECS 2009, October 20–22 2009, San Francisco, USA.

[208] Nolte W. L., Kennedy B. C., and Dziegiel R. J. Jr., Technology Readiness Calculator, unpublished. URL: http://www.dtic.mil/ndia/2003systems/nolte2.pdf [retrieved February 15, 2011]. Tool available at URL: https://acc.dau.mil/communitybrowser.aspx?id=25811. [accessed February 15, 2011].

[209] Zadeh L.A., Fuzzy Sets, *Information and Control*, Vol. 8, No. 3, pp. 338–353, 1965.

[210] Kaufmann A., Gupta M. M., Introduction to Fuzzy Arithmetic, Van Nostrand Reinhold Company, New York, 1985.

[211] Klir G. J., and Yuan Bo, Fuzzy Sets and Fuzzy Logic, Prentice-Hall, NJ: Upper Saddle River, USA, 1995.

[212] Kaufmann A., Gupta M. M., Fuzzy Mathematical Models in Engineering and Management Science, Chapter 13, North-Holland, Amsterdam, The Netherlands, 1988.

[213] Berthouex P. M., Brown L.C., Statistics for environmental engineers, CRC Press, Boca Raton, FL, pp. 49–51, 2002.

[214] Nelson W., Applied Life Data Analysis, Wiley, Hoboken, NJ, pp. 113–118, 2003.

[215] Castet J.-F., Saleh J. H., Satellite Reliability: Statistical Data Analysis and Modeling, *Journal of Spacecraft and Rockets*, Vol. 46, No. 5, pp. 1065 – 1076, 2009.

VITA

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