Developing Commercial Transportation Capability through Technological Milestones

Ronald H. Freeman
Northcentral University
Prescott Valley, AZ
ronhfreeman@yahoo.com

Abstract - *National Institute Rocket Propulsion Systems (NIRPS) assessment of over 40 industry studies and historical analysis of performance reliability and costs in rocket engine development indicate long-term industry downsizing since 1979 and a shortage of new solid and liquid propulsion programs that threatens U. S. leadership in rocket and missile propulsion. This paper presents a systematic review of commercial spaceflight industry current market revenues and of different* technological milestone *models currently employed by new space companies to vitalize the propulsion industrial base. The paper outlines the case for lowering propulsion development costs through readiness management of technology portfolios in propulsion system development projects.*

Keywords: Rocket propulsion systems, complex adaptive systems, technological risk management, technology portfolio management, technological readiness level management.

1 Background

Technology over time reduces production costs [1], while performance increasingly couples to the system's technical complexity. Space launch vehicle (SLV) manufacture constitutes assembly of subsystems, component parts and interfaces that reflect complexity of different technologies [2]. SLV performance failure rate reflects the system's complexity to impede functional or utilizable readiness. Missing or loose structures, engine failures or pre-mature shutdowns, fuel leaks, docking vehicle malfunctions are examples of space launch vehicles' poor performance. From the perspective of Critical Realism Theory, both barriers and opportunities to propulsion subsystem reliable performance and spiraling costs are rooted in entangled web of equipment legacy, tacit practices, and historical policies weighing on *higher, farther, faster* disruptive innovative technology. Developing large-scale complex systems combine many technologies from a cross-section of different disciplines. Complexity of the systems pairs with continuous technology development, a costly R & D investment [3]. Complexity of the systems demands increasingly greater innovation capability that compound expectations of what technology is capable in achieving. At the same time, complexity causes below-par performance of the systems. Managing system complexity demands exploring the factors it reflects, including functionality, number and type of technologies related to the subsystem's risk uncertainty, and the readiness for subsystem integration.

2 Introduction

The perspective of critical realism provides a paradigmatic orientation how to examine experiential complexity during organizational process of technology adoption. The three-fold stratification system of empirical (observed), actual (observed and unobserved) and real (unobserved) layers, in the Theory of Critical Realism describes the morphogenesis of structures and operations observed and experienced. Relevant subsystem parts and their mechanisms manifest and emerge from processes and simpler structures in the unobserved layer of production processes. On examination, the structures link internally with other components to effectually manifest as events and processes in the empirical layer [4]. Organizational norms and practices, management and comptroller positions, and labor relations in general emerge to condition and provide functional order in subsystem manufactured operation. Moreover, conscious, observable activities directed toward intentional goals, contribute to unconscious, unintended organizational reproduction for future rounds of the manufacturing politico-technical activities [5].

Propulsion subsystems represent over half of the launch vehicle subsystem failures [6]. The high levels of complexity associated with propulsion subsystems often provide opportunities for failure. Many of these failures can be prevented through proper design, testing, and operation [7]. Launches of US-built space vehicle from1984 to 2004 have been riddled with propulsion subsystem problems causing 52 percent of all launch failures. The Futron Corporation study summarizes the root causes of 25 launch failures out of 470 total orbital launches during the same time period [8].

Space launch vehicle propulsion subsystems built during the time period represented 60 vehicle variants from about 12 vehicle families containing similar parts: solid motors for Pegasus and Taurus, and upper stage for Atlas and Titan. Liquid propulsion failures occurred due to insufficient thrust or premature shutdown. Comparatively, failures in the solid motors were due to breaches in the shell or loss of thrust vector control related to hydraulic fluid depletion.

Besides propulsion reliability studies, consideration must be given to the state of propulsion system manufacturing. The National Institute of Rocket Propulsion Systems researched the factors for the decline in rocket engine development. It acknowledged low demand due to the Space Shuttle Program and the Constellation Program ending, and projections for the commercial launch market still unrealized. The Department of Defense's EELV program is the primary provider of launch vehicles for military and intelligence satellites. According to the US Government Accountability Office's EELV Report to US Congress [9], launch services is estimated to cost 19 billion dollars from 2013 to 2017, and the program will cost 46 billion dollars through 2030. Under FAR Part 15 that requires limited insight into contract costs, DoD had regularly awarded Boeing and Lockheed-Martin (later ULA) for Delta IV and Atlas V launch services, respectively. In 2009, EELV prices skyrocketed that the Tiger Team of Air Force, DoD, NRO (National Reconnaissance Office) and NASA officials agreed to develop a new acquisition strategy that includes no *block-buy* contracts; discontinuance of waivers in required reports of pricing and cost data; open competitive bids for launch contracts; and, single launch contract awards.

Privatized efforts in the space launch vehicle industry started with Robert Truax rockets in the 1930s. Later efforts from 1960s to 1990s, included designs of suborbital vehicles, and multi-stage orbital vehicles by companies undercapitalized for project development [10]. Space Sciences completed successful launch tests of Conestoga I in 1982. Orbital Sciences first launched the Pergasus, solid-fueled vehicle, in 1990. Beal Aerospace developed BA-810, hydrogen peroxide/ kerosene fueled vehicle, had to compete with NASA's EELVs. Kistler Aerospace's K-1 was a re-usable 2-stage launcher to serve LEO constellation market. Amongst these successes, the privatized industry was riddled with test flight failures, project cancellations, and company bankruptcies or closures.

Utilization of NASA's Space Act Agreements helps facilitate US private industry to demonstrate crew and cargo space transportation capabilities to achieve reliable, cost-effective access to low-earth orbit. When partnered with few large aerospace companies on a *cost plus contract fee* basis, NASA defined what and how partners develop space capability [12]. Comparatively, when NASA initiatives develop space exploration projects with many providers, and private and public users, contracts are negotiated on a *fixed fee* basis. NASA still defines the *what* but industry decides the *how* in developing space capabilities.

3 Technology Development Risk

Technology development risk is important to determine the feasibility of the promised performance benefits. It measures the probability of a technology maturing toward an operational state as a function of time. The probability of project failure is measured by technical failure of performance, as well as programmatic failure of cost and schedule [11], all of which manifest from both observed and unobserved structures and inter-structural relations.

To emphasize superior performance at economical cost savings, technological replacements have been utilized. Plasma-based technology to produce propulsion for velocities greater than achievable with chemicals (Ad Astra Rocket Company) has demonstrated test-proven superior performance [12]. Additively manufacturing a casing body into a non-bonded, non-joint bolted single piece combustion chamber constituted of material functioning as combustion-consuming solid rocket fuel [13] provides propulsion at great cost savings. However, technological performance and costs reflecting subsystem incorporation of multiple technologies, improve efficiency when synchronized for readiness maturity levels. Manufacturing readiness also entails scheduling the readiness of other equipment and facilities when production delays occur. According to Government Accountability Office (GAO), the lack of manufacturing knowledge at key decision points is the leading cause of cost growth and schedule slippages in major DoD acquisition programs [14]. Although manufacturing status and risk evaluations have been utilized in defense acquisitions, they were also employed in technology development. U.S. Department of Defense Instruction 5000.02, *Operation of the Defense Acquisition System* (December 8, 2008) established target maturity criteria to measure risks associated with manufacturing processes. Manufacturing Readiness Levels (MRLs) create a measurement scale and vocabulary for assessing and discussing manufacturing maturity and risk. Both manufacturing readiness metrics and technology readiness metrics manage risk areas of immature product technologies and immature manufacturing capability to improve cost, schedule and performance in subsystem manufacture NASA has long used Technology Readiness Levels (TRL) approach. TRLs assess the maturity of a particular technology and are used to track technologies in development and their transitioning into production processes.

High performance propulsion subsystems are infused with advanced enabling technologies to yield a competitive advantage. Key propulsion parameters for engine chamber pressure, area ratio, and oxidizer/fuel ratio, are optimized and plotted to show impacts to engine mass and overall vehicle mass [15]. Among the factors that characterize technology risk for subsystem development is uncertainty that technologies constituting the subsystem's technology portfolio will reach maturity for subsystem integration, and that technical performance measures will be met [16]. Risk analysis and response planning should be done during the initial phase. Assessing development difficulty includes evaluating the technological readiness level gap (initial to TRL 6) and the research and development (R & D) degree of difficulty. Maturing the technology is a time- as well cost- consuming process. NASA specified that technologies should mature to TRL 6 as defined in Table 1 before a mission assumes responsibility for the technology [17].

Table 1. Technology Readiness Levels

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

However, TRLs fail to completely represent the difficulty of integrating the subject technology into an operational subsystem, and fails to assimilate a comparative analysis technique for alternative TRLs. A *TRL* related to a single technology within a subsystem context implements differently than when the interplay between multiple technologies of a single technology portfolio is introduced. System Readiness Levels (SRL) addresses the concerns of integration, interoperability, and sustainment of multiple technologies from a system's operational perspective. Different technologies mature at different rates. Therefore Integration Readiness Levels (IRL), shown in Table 2, intermediately function as a of TRL-IRL-TRL readiness to prepare for system's simultaneous implementation of multiple technologies. IRL measures the interfacing between compatible interactions for different technologies and a consistent comparison of their TRLs at integration points prior to subsystem incorporation. IRLs are used to describe the integration maturity of a developing technology with another technology that is developing or is already mature. Whereas TRL assess risk associated with developing technologies, IRLs assess risk related to their integration. With increased performance-driven system complexity, such IRL methodologies provide for TRLs to collectively combine for system complexity.

Table 2. Integration Readiness Levels

IRL	Definition
7	The integration of technolkogies has been verified and validated with sufficient detail to be actionable.
6	The integrating technologies can accept, translate, and structure information for its intended application.
5	There is sufficient control between technologies necessary to establish, manage, and terminate the integration.
4	There is sufficient detail in the quality and assurance of the integration between technologies.
3	There is compatibility (i.e. common language) between technologies to orderly and efficiently integrate and interact.
2	There is some level of specificity to characterize the interaction (i.e. ability to influence) between technologies through their interface
1	An interface (i.e. physical connection) between technologies has been identified with sufficient detail to allow charaterization of the relationship.

Operational system readiness level considers the different dynamics of each assembled subsystem, hence the need for a Systems Readiness Level (SRL) for the following reasons: (1) there is multilateral causality among the subsystems functioning within the system and the environment, at large; (2) one set of initial conditions can exhibit in different final states; and (3) performance uncertainty relates to information flow between component subsystems. The SRL index relates to the phases of development in the life cycle management model of manufacturing.

4 Discussion

The space economy is much wider than the launch vehicle industry. It can be defined by its products (satellites, launchers, et c), by its services (e.g. broadcasting, imagery/data delivery), by its programmatic objectives (e.g. military, robotic space exploration, human spaceflight, Earth observation, telecommunications), by its value chains (from R & D to end- user commercialization), and by its impact of direct and indirect benefits [21].

The Tauri Group collaborated with the Commercial Spaceflight Federation (CSF) to study revenues, quantity of investments, and types and sources of investment in the commercial spaceflight industry. With the proprietary dataset of industry metrics maintained, the Tauri Group developed a model of industry revenues represented in three different levels of activity. The CSF company membership numbered 31, as of September, 2010, of which nine were launch vehicle developers. In a 2006-2009 study, the Tauri Group modeled commercial spaceflight industry revenues to accommodate different levels of activity. Level I represent low revenues for orbital and suborbital personal spaceflights, increasing from $142M in 2006 to $258M in 2008 [22]. Global demand cargo equivalents, 270 seats annually, increased from year one to over 500 in year 10 [23]. Level II includes hardware and support services that support commercial spaceflight services, sales of commercial-spaceflight-related products and services to non-commercial customers (e.g. solid rocket markets). Level III tracks revenues of industry member companies, with revenues increasing from $24M in 2006 to over $1.4B.

Commercial opportunities exist in the satellite market; NASA missions and projects; the market of orbital research labs for research and experimentation with microgravity; market of asset servicing per reduced lifespan of satellites related to lower operational lives and damage associated with space debris requiring repair or refurbishment; asteroid mining; and space tourism market. In a 2006 Stanford University study, investor horizon averages 5-8 years for profitability [24]. Global space market is estimated at $200B annually. The total investment in the industry is estimated at $1.51 B through mid-2009, of which over half was from individuals and investors, and the remainder split between government and private equity investment.

Space underwriters match premium income against risk of losses, estimated at $400M revenues in 2012 [25]. Space insurance for most space risks are covered by several underwriters. Space launch insurance policies provide coverage from pre-launch to several years into satellite lifespan. Some underwriters also cover third party liability risk associated with launches and satellite operations and related pre-launch cargo.

5 Conclusions

The launch vehicle industry is predicated on cheap access to space. The history of small, entrepreneurial aerospace companies demonstrate the toll of high project costs, as many were forced into bankruptcy. New space companies envision a timeline for space exploration utilizing fixed price contracts and Space Act Agreements with NASA. Commercialization of the launch vehicle industry depends on the reliable provision of rocket engines. The reasons for the decline in rocket engine development are multifactorial. However, the need for propulsion industry growth will likely match the demand space tourism promises. Further SLV growth will depend on (1) how the new space companies leverage revenues of space tourism and payloads transports for more long-term or higher-cost space exploration projects; (2) cost savings from new technologies; (3) leveraging performance capabilities with readiness levels to integrate and incorporate multiple technologies for system operation reliability; and (4) innovative business planning that coordinate reinvesting of short-term revenues into medium- and long-term missions.

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