

Product Lifecycle Management and the Quest for Sustainable Space Explorations

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Product Lifecycle Management (PLM) is an outcome of “lean” thinking to eliminate waste and increase productivity. PLM is inextricably tied to the systems engineering business philosophy, coupled with a methodology by which personnel, processes and practices, and information technology combine to form an architecture platform for product design, development, manufacturing, operations, and decommissioning. In this model, which is being implemented by the Engineering Directorate at the National Aeronautics and Space Administration’s (NASA’s) Marshall Space Flight Center, total lifecycle costs are important variables for critical decision-making. With the ultimate goal to deliver quality products that meet or exceed requirements on time and within budget, PLM is a powerful concept to shape everything from engineering trade studies and testing goals, to integrated vehicle operations and retirement scenarios. This paper will demonstrate how the Engineering Directorate is implementing PLM as part of an overall strategy to deliver safe, reliable, and affordable space exploration solutions. It has been 30 years since the United States fielded the Space Shuttle. The next generation space transportation system requires a paradigm shift such that digital tools and knowledge management, which are central elements of PLM, are used consistently to maximum effect. The outcome is a better use of scarce resources, along with more focus on stakeholder and customer requirements, as a new portfolio of enabling tools becomes second nature to the workforce. This paper will use the design and manufacturing processes, which have transitioned to digital-based activities, to show how PLM supports the comprehensive systems engineering and integration function. It also will go through a launch countdown scenario where an anomaly is detected to show how the virtual vehicle created from paperless processes will help solve technical challenges and improve the likelihood of launching on schedule, with less hands-on labor needed for processing and troubleshooting.

I. Introduction

Sustainable space exploration solutions demand that all lifecycle phases be optimized. Adopting PLM, which has been used by the aerospace and automotive industries for many years, for spacecraft applications provides a foundation for strong, disciplined systems engineering and accountable return on investment. PLM enables better solutions using fewer resources by making lifecycle considerations in an integrative decision-making process. This paper combines the overarching perspectives of a renowned PLM expert, along with the experience of engineers at NASA’s Marshall Space Flight Center, who are implementing these processes and practices real-time.

As the nation moves from an industrial-based society to one where information is more prized as a valued commodity, future NASA programs and projects will benefit from the experience being gained today for the exploration missions of tomorrow. In retrospect, Gordon Moore, one of Intel’s founders, noticed that over the course of a year and a half, a microprocessor’s computing capability approximately doubled. His observation, now dubbed Moore’s Law, proved rather prophetic, as the improvements in modern microprocessors do indeed tend to follow this pattern.¹ Following this observation, it is no surprise that technological capabilities have advanced at an exponential rate throughout the 30-year lifespan of the Space Shuttle, which provides a foundational example of the

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impact of lifecycle costs, as the program draws to a close in 2011 (Figure 1). From Saturn, to Shuttle, to future space transportation systems, data and information management are keys to mission success.



Figure 1. America's Space Shuttle has flown with distinction for over 30 years (STS-132).

Where NASA engineers once used slide rules and paper drawings to design rocket technologies, today's workforce has the benefit of powerful electronics equipped with sophisticated mathematical computing capabilities, robust computer aided design programs, and realistic three-dimensional models in their portfolio of tools. As NASA begins a new era, the amount of data to be created, managed, and used throughout the lifecycle of a product is ever increasing. Add to that the risky nature of the space business, and it becomes imperative to maintain an authoritative data set for use across all disparate aspects of a project. This fact became especially pertinent given NASA's acquisition strategy for the Ares Launch Vehicle, part of the Constellation Program, which was to design and integrate the Upper Stage in house, through collaboration with industry partners. To realize this strategy required that NASA find ways to share data with industry, and required that Marshall Space Flight Center's Engineering Directorate transition from paper-based to electronic change management processes. In this regard, applying PLM serves to integrate not only hardware and software deliverables, but also various discipline teams across government, industry, and academic partnerships. NASA has recognized the necessity of this paradigm shift and has begun to take actions to move toward applying the PLM methodology across the Agency's programs and projects.

NASA's existing systems engineering policies provide methodologies for ensuring that the activities conducted for each element of a vehicle are consistent and the finished products will integrate as intended into the space system.² However, better use of digital tools coupled with efficient management techniques, both central elements of the PLM methodology, can help increase productivity and effectiveness of the systems engineering and management activities that NASA and its partners conduct. The value of these improvements has already been demonstrated by the automotive industry, which adopted PLM with great success out of the necessity to optimize the way it designs, develops, tests, and safely operates vehicles.

As historian Stephen Johnson reports in *The Secret of Apollo*, “Technical failures of aerospace projects are hard to hide. Rockets and missiles explode. Satellites stop sending signals back to Earth. Pilots and astronauts die. To the extent that systems management helped prevent these events [during Apollo], it must be deemed a technical success. Systems management methods such as quality assurance, configuration control, and systems integration testing were among the primary factors in the improved dependability of ballistic missiles and spacecraft. Missile reliability ... increased from the 50% range up to the 80 to 95% range, where it remains to this day.”³ PLM is a supporting methodology and suite of tools for quality control and systems management for NASA’s missions of advanced technology development and demonstration, as well as future flights beyond Earth orbit by human and robotic explorers alike.

Adopting the PLM systems management approach within NASA, along the same lines used by industry today, is expected to result in significant value added through reduced risk, fewer wasted resources, and the production of a higher quality product with fewer cost and schedule impacts. The narrative below describes how NASA’s systems engineering processes and the PLM approach are synergistic, and how coupling the two can advance NASA’s capability to handle and use data throughout the product lifecycle, effectively creating a knowledge management foundation in the process. In addition, this paper explores how Marshall Space Flight Center has taken significant steps toward implementing a PLM strategy for the center.

II. NASA’s Systems Engineering Philosophy and Approach

Because the missions that NASA undertakes are especially unique, and as a result risky, cultivating a world-class systems engineering capability proves essential. NASA places a strong emphasis on the art of systems engineering because it requires skills beyond just applying the rules of engineering and physics, to grasping the “big picture” and ensuring that once all the components and elements, which are usually designed by different organizations located across the country, are produced, they will work together as an operational vehicle.

Systems engineering increases communication between discipline teams and project managers through formal channels, such as approval boards convened at milestone reviews, and informal dialogue through working groups and discipline-based communities of practice. It provides a framework for risk reduction and mission success built on standardized principles and practices used in a collaborative work environment, where hardware and software are united from requirements to retirement and can be replicated using carefully documented processes.

Beyond that, systems engineering reduces risk by providing a strong linkage between and among disparate engineering disciplines, from aerodynamics and avionics, to mass properties and thermal control. Through systems engineering, trade study analyses are performed to determine the optimum solutions that fulfill customer and stakeholder requirements, focusing on the “-ilities,” such as reliability, maintainability, supportability, operability, and affordability.

According to the NASA policy on systems engineering processes and requirements, “The emphasis on systems engineering is on safely achieving stakeholder functional, physical, and operational performance requirements in the intended use environments over the system’s planned life within cost and schedule constraints.”⁴ When engineering new technologies destined for new systems, NASA looks to its lessons learned from previous successes and failures, as well as best practices from industry and other government agencies, to inform activities.

NASA’s systems engineering regulation gives specific requirements and processes suitable for performing complex missions within schedule and budget constraints. The goal is to apply “a systematic, disciplined engineering approach that is quantifiable, recursive, iterative, and repeatable for the development, operation, maintenance, and disposal of systems integrated into a whole throughout the lifecycle of a project or program.”⁵ This applies both to systems engineers, often embodied in a network of chief engineers, and to the technical teams developing the subsystems that must be integrated into the overall whole.

The major three tenets of NASA’s systems engineering framework are: workforce, common technical processes, and tools and methods. Thus, the approach to systems engineering at NASA includes defining processes, while adopting tools and methods to carry out those processes, and then training the workforce to use the processes, for a consistent approach as possible across the Agency — and these track consistently with the PLM framework.

A. Lifecycle

NASA has defined 17 key systems engineering processes throughout the lifecycle of the product. These processes and their relationships to one another are shown in Figure 2. These process steps are broken down further into three categories that correspond to system design processes, product realization processes, and technical management processes, which crosscut the design and development of the product. These categories, in turn, relate to various lifecycle steps and stages addressed by PLM.

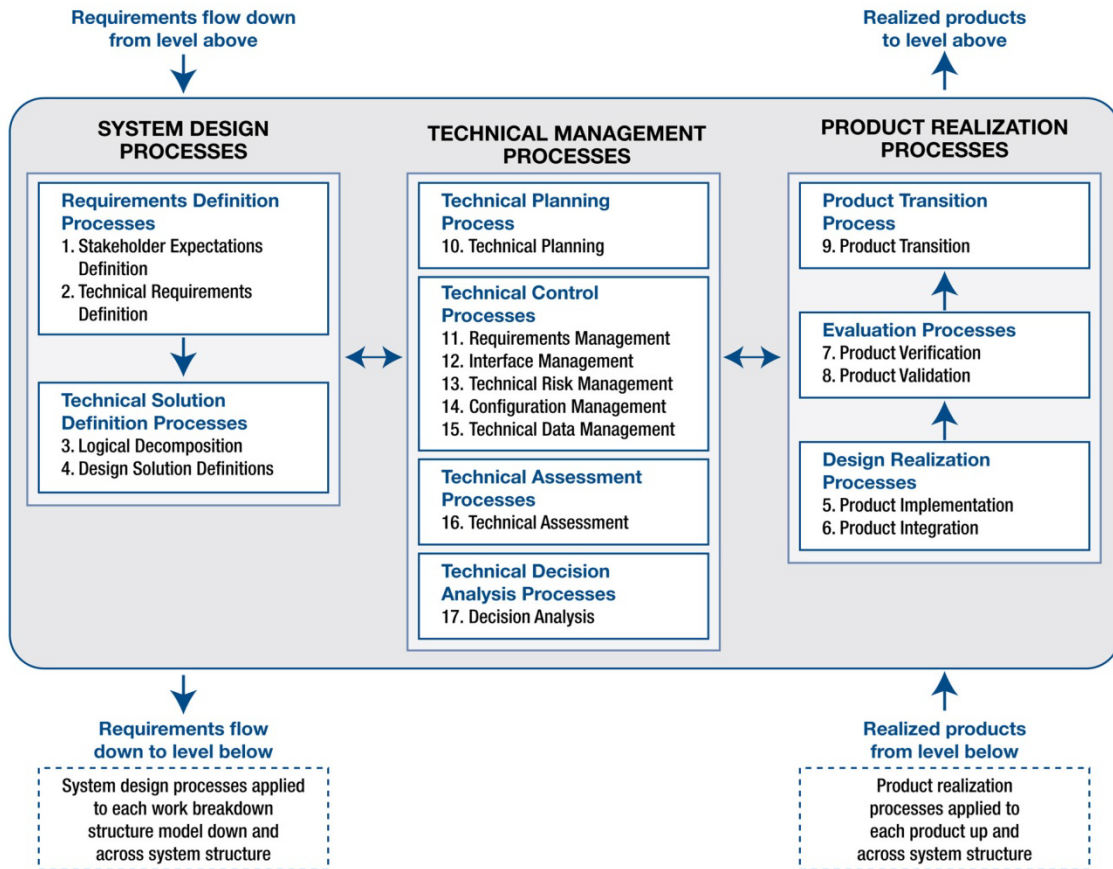


Figure 2. NASA systems engineering engine flowchart (SP-6102).

The systems engineering processes are used throughout the product lifecycle to ensure that overall goals are being realized. Each project phase is marked by a number of data deliverables that undergo systematic reviews performed by internal and independent experts who help guide decisions at critical junctures. The systems engineering engine (refer to Figure 2) illustrates a top-down methodology for product design and a bottom-up approach to integration, testing, and development of products. The technical management processes in the center of the engine address the planning and analysis required for the design to come to fruition. The systems management processes include activities such as risk management, configuration management, and data management, as well as decision analysis.

B. Milestones

The NASA program/project lifecycle breaks down the major activities required to accomplish a mission into distinct phases, separated by key decision points (Figure 3). Near-term milestones help the technical team and system managers understand how to proceed and to gauge requirements during development. These phases correspond to higher-level lifecycle stages of formulation, approval, and implementation.



Figure 3. NASA program/project lifecycle phases and stages (SP-6102).

At each major phase transition, milestone reviews are held to capture the status of the design at that point, be it spacecraft, launch vehicle, or major subset of them. These reviews evaluate information to ensure that the team and the product are ready to progress to the next phase of development. The major systems engineering/ program/project reviews are listed in Table 1 below, which also gives top-level success criteria. These examples are provided to orient a top-level view of the business of engineering at NASA relative to the PLM strategies described below.

Table 1. NASA milestone review summary (NPR 7120).

Review Title	Review Purpose/Outcome
System Requirements Review	Assures that requirements are properly defined, verifiable, and implemented, are traceable, and that the hardware and software are designed and built to the authorized baseline configuration.
Preliminary Design Review	Provides completed design specifications, the identification and acquisition of long-lead items, manufacturing plans, and lifecycle cost estimates; the design is 30% complete and element specifications are baselined.
Critical Design Review	Discloses the complete system in full detail; ascertains that technical problems and design anomalies have been resolved; and ensures that the design maturity justifies the decision to begin fabricating/manufacturing, integration, and verification of mission hardware and software. The design is 90% complete.
Design Certification Review	Serves as the control gate that ensures the system can accomplish its mission goals. Requirements are verified in a manner that supports launch operations.
Flight Readiness Review	After the system has been configured for launch, the Flight Readiness Review process examines tests, demonstrations, analyses, and audits that determine the system's readiness for a safe and successful launch and for subsequent flight operations. The Project Manager and Chief Engineer certify that the system is ready for safe flight.

Managing the knowledge generated throughout the project lifecycle phases, as well as all the design changes, is imperative to ensuring that the final product works effectively. Although NASA has seen advances in information technology for managing, sharing, and retaining engineering data, a great deal of time and energy is still spent

resolving inconsistencies and problems. There remains considerable room for improvement. Minimizing risk in all mission phases is essential to continued success, especially as the Agency transitions its approach to focus on space transportation architectures that have yet to be defined. By better managing the information *and* knowledge associated with the design, development, and operations of space technologies, while consistently infusing lessons learned throughout the product lifecycle to help reduce risk, the outcome will be a more accurate and timely snapshot of the product status through virtual models and complete access to authoritative product data handed off from the as-designed, to the as-built and as-operated stages. Examining the tenets of PLM will help show the applicability of the PLM methodology to the tried-and-true systems engineering and management approaches codified in NASA doctrine.

III. PLM Reduces Risk through Integration

In the literature, PLM is described as “an integrated, information-driven approach comprised of people, processes/practices, and technology to all aspects of a product’s life, from its design through manufacture, deployment and maintenance—culminating in the product’s removal from service and final disposal. By trading product information for wasted time, energy, and material across the entire organization and into the supply chain, PLM drives the next generation of lean thinking.”⁶ PLM is not just a software package or tool, but rather a methodology that leverages an organization’s workforce, practices, and information technology tools to manage the data produced throughout the entire lifecycle of a product, thus allowing for robust virtualizations, “informational or bit-based representation[s] of a physical or atom-based object,” of the product that make troubleshooting easier and increase the likelihood of mission success.⁷

PLM relates to people and the processes and practices that they use on an IT platform that is secure, flexible, and responsive (Figure 4). The aerospace enterprise depends on this trinity to shape data into knowledge that informs everything from requirements development, based on figures of merit and design reference missions, to engineering trade studies at the component, element, and system levels. This framework of people, processes and practices, and technology are at the center of the product lifecycle. The PLM approach both contributes data to the product lifecycle as it unfolds, as well as integrates data to provide inputs for the next product lifecycle phase.

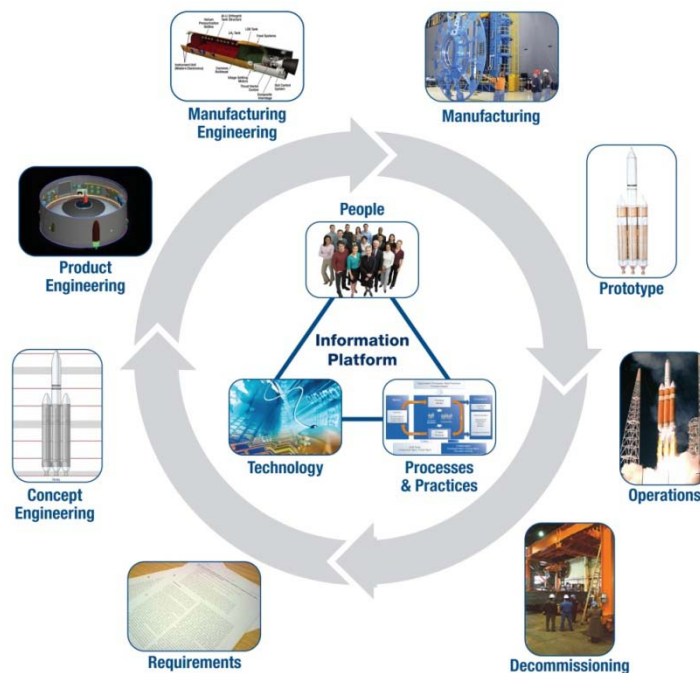


Figure 4. PLM addresses and integrates every phase of a product’s development, use, and disposal.

IV. The Importance PLM to Space Exploration

Managing the huge amounts of complex engineering data required for NASA projects has always been a challenge, and conducting a project in the most efficient way possible allows for greater probability of a successful outcome on schedule and within budget. While commercial entities have adopted PLM out of necessity for increased productivity and cost reduction, NASA programs, which often culminate in building only one or two products, still rely largely on a document-based approach to product management. By managing engineering data electronically, a robust PLM implementation will allow NASA to easily compare the as-designed, as-built, and as-operated systems in a virtual environment that makes troubleshooting in the real-world environment easier and quicker, ultimately reducing risk and maximizing the use of limited resources, from budget to workforce. Implementing robust PLM platforms has proved paramount to the success of the automotive industry, which began adopting the methodology out of necessity to reduce waste, cut costs, improve quality, and increase profit, and today, nearly all major auto corporations employ a PLM framework.

For example, despite being in dire financial straits, General Motors (GM) used PLM to successfully digitally design, engineer, and manufacture the Chevy Volt, a highly innovative and leading edge electric car that will be available this fall. This project required new technologies, new engineering approaches, and new manufacturing processes and facilities. Using traditional methods, this development would have been impossible to accomplish within the allotted time and resource constraints.

It is important to remember that NASA accomplishes innovative, complex missions for about \$18 billion a year, less than one percent of the entire federal budget, which underscores the importance of adopting PLM to increase efficiency and quality, while reducing costs. As stated earlier, PLM reduces risk by integrating the workforce's processes and practices to deliver consistently high quality products, all with the stakeholders' requirements as the basis. From cradle to grave, the necessary information is at the fingertips of the appropriate workforce and tailored to the applications and formats they need. Perhaps more importantly, stakeholders are able to visualize the connections between information from different phases and gain a more comprehensive view of the entire system.

Information technology is, in essence, a partner as it enables a host of business functions, while it unites (or divides) discipline and systems engineering teams. In the PLM framework, IT enables robust systems engineering and data management processes to be realized in a virtual environment. Thus, engineers no longer create paper drawings, but rather, visualize the virtual design in cyberspace using the power of modeling and simulation to refine work before building and testing hardware. Currently, two-dimensional drawings are checked in three-dimensions and manufacturing processes are checked using hardware mockups; however, transitioning to managing this process virtually would provide significant improvements to the way that NASA does business and is critical to staying current with industry.

As former NASA administrator Robert Frosch wrote, "Systems, even very large systems, are not developed by the tools of systems engineering, but only by the engineers using the tools."⁸ The PLM methodology supports Frosch's sentiment, in that it relies on the knowledge resident in engineers, but also provides a set of integrated applications by which data can be captured, managed, applied, and retained, allowing an experienced workforce to transcend the tyranny of tools and become more creative in its critical thinking skills.

A. NASA's PLM Implementation Status

While NASA moves into an era of increased collaboration with international and commercial partners as well as among its field centers, it is important that project teams share access to a single source of authoritative data and, conversely, that data flows freely but securely among geographically dispersed project teams. Maintaining a robust PLM system can break down organizational information silos and foster the capture, sharing, and retention of both data and its counterpart — knowledge. NASA has recognized the importance of this and is making efforts to develop a flexible, yet effective PLM approach for the Agency, and has recently included a Product Data Management (PDM) and PLM requirement in the NASA Policy Directive 7120.4D, “NASA Engineering and Program/Project Management Policy,” which calls for “apply[ing] disciplined, collaborative processes and systems to identify, acquire, and control product data throughout the project lifecycle for Space Flight programs and projects.”⁹

PLM is especially important in technology development programs, where disparate parts must come together and work flawlessly in highly complex systems. The PLM risk-reduction approach ensures that research and development investments are traceable to sources that may no longer be in existence by the time long-lead spacecraft are fielded. Using engineering business standards, processes, and tools throughout the technology development cycle — from concept and trade studies, to manufacturing and operations — this approach improves the likelihood that products delivered by commercial and government partners can be synchronized into an integrated whole that is truly more than the sum of its parts.

As a convention for collaboration, NASA has established communities of practice as part of its Agency-level knowledge management strategy. These communities revolve around engineering disciplines, systems engineering, risk management, and a variety of other specialties. Knowledge management tools link information generated through electronic mail and informal discussions to project-specific data. This application can be integrated into the PLM platform.

Although the Agency has moved toward managing data electronically, the practice is neither widespread nor standardized. In addition, many disparate sources of information still exist, leaving questions about data authority and integrity. As it moves toward a digital environment, NASA's systems engineering processes are still largely carried out through physical documents or through a combination of physical documents and virtual data.

From this macro-environment, the Marshall Space Flight Center's Engineering Directorate has implemented certain aspects of PLM into its engineering culture and climate. As a point of reference, Figure 5 shows how a broad sampling of the systems engineering efforts conducted by Marshall Engineering align with the phases of product lifecycle.

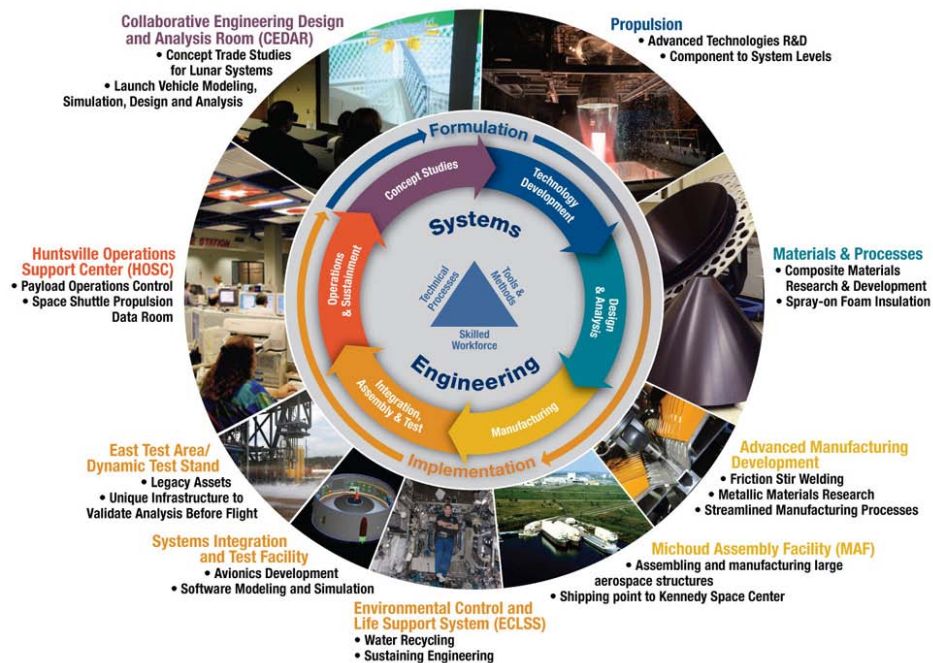


Figure 5. Marshall Engineering supports every facet of the product lifecycle.

By its very nature, NASA is on the leading edge of process improvements that lead to product improvements facilitated by applying PLM strategies. Marshall's Technical Management Office in the Engineering Directorate actively consults with PLM experts and has undertaken several important initiatives that are helping to lay the foundation for establishing a PLM framework by investing in institutional capabilities that are adaptable to many shapes and sizes of projects.

The Engineering Technical Management Office at Marshall has implemented the Design and Data Management System (DDMS) in all new projects at MSFC. As an automated system for the process of drawing release and configuration control, DDMS gives users total electronic access to engineering drawing data and has drastically reduced the time it takes to review and release engineering drawings and models. In addition, the DDMS application is helping move the Marshall Center as a whole toward a paperless three-dimensional model-centric approach, versus the traditional drawing-centric environment. In addition, this office oversees development of the Marshall Engineering Knowledge Management System, which customizes commercial off the shelf software applications to provide a robust capability for collaboration, knowledge sharing, and knowledge capture, as well as an enterprise and expertise search engine.

While PLM has had a positive effect on bringing this important government capability to parity with commercial industry, future block improvements are under consideration as Agency goals and objectives are formulated and funded. Given below are several compelling reasons to go forward with PLM at the Agency level, using the experience gained by Marshall Engineering over the last several years.

B. Benefits of Implementing PLM for Next Generation Space Technologies and Transportation

With NASA's changing missions, now more than ever, the Agency will have to manage the design and development of more complex and diverse science and exploration missions. A strong PLM implementation strategy supports NASA's systems engineering philosophy and approach (Figure 6), while it provides an integrated solution to data management throughout the lifecycle, from technology development to operation and retirement.

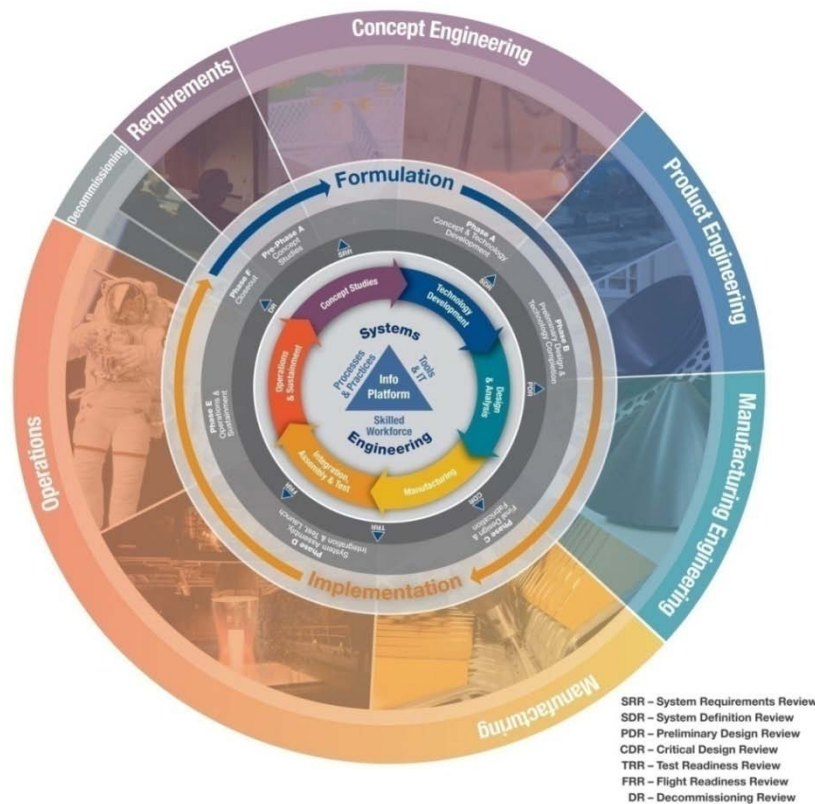


Figure 6. PLM supports NASA's systems engineering phases and milestones, providing formal and informal channels for vertical and horizontal integration.

NASA projects are extremely unique, as is the highly specialized work done at the various NASA Centers in support of Agency missions. Implementing an Agency PLM strategy has the potential to give NASA engineers direct access to accurate, reliable data from disparate locations, while strengthening its systems engineering approach. Adopting PLM could allow NASA to move away from a document-centric culture to a digital-based enterprise, where the pieces of data an engineer needs are embedded and available in the tools he or she uses to do their day-to-day work and to make accurate, appropriate decisions. In addition, the ability for all personnel working on a project to be able to access authoritative data from a single source can help ensure the integrity of engineering data used for design, fabrication, operation, and troubleshooting.

Longer term, PLM should help ensure that the changes between the as-designed, as-built, and as-operated versions of a vehicle are tracked and clearly traceable. PLM will give engineers a virtual model created from authoritative data, so that it accurately reflects the current vehicle configuration at any given time. Ensuring the data integrity across the lifecycle of any type of complex product or technology is crucial to ensuring that changes made at one phase in the lifecycle are carried through to all the other stakeholders at various points in the lifecycle. It ensures that as changes are made to the actual product, they also are made to the virtual product, so data remains accurate and ensures that models and simulations are as close as possible to the as-operated hardware/software. Since the virtual product data is constantly being updated, engineers save time and effort by not having to search for data nor recreate the data they need. Adopting a methodology such as PLM will allow a large organization such as NASA to save time and money in the design, development, and troubleshooting, while enhancing innovation and knowledge creation.

C. Launch Scenario

As discussed in this paper, adopting the PLM methodology affords many benefits in terms of its design, development, operations, and troubleshooting efficiency and success. Looking at a typical problem that might occur on launch pads helps put the concrete benefits of adopting PLM into perspective.

A future heavy-lift vehicle is on Launch Pad 39B at the Kennedy Space Center with 48 hours to go before launch when a sensor reading indicates a problem. The sensor on a critical valve in the upper stage engine is showing a reading indicating an anomaly. Quickly, the Mission Team assembles propulsion and manufacturing experts to evaluate the problem.

The team zeroes in on the area of the valve on a virtual image of the vehicle on a large LCD and visually explores the hardware and its surrounding components. They look at the as-designed components and juxtapose them with the as-built hardware now in the launch vehicle sitting on the pad. They review the manufacturing data on each process step that the valve went through and notice that the measurements captured on a valve inlet tended toward its maximum tolerance.

Next, they call up the design engineering data on the valve in order to look at the specification. The simulation data indicates that there is a potential for problems if the valve inlet and its coupling are at the high end of the tolerance. The team looks at the coupling design and at the as-built coupling on this launch vehicle. It, too, is at the high end of its tolerance.

The team then accesses the inventory of as-built valves, limiting their search to those at the low end of the tolerance, and selects a new one. Technicians replace the component and the sensor returns to normal. The elapsed time to analyze and resolve the anomaly is around three hours, versus three days or even three weeks. Finally, the team updates the valve requirements that would trigger an exception for any valve-coupling that approaches tolerance limits in each future launch vehicle. The probability of an on-time launch is dramatically improved using the PLM platform (Figure 7).



Figure 7. Launch concept of a notional heavy-lift vehicle.

What made this possible is the existence of not only a physical launch vehicle sitting on the launch pad, but also a digital launch vehicle that allowed personnel across multiple locations to access all the information they needed to analyze and resolve a problem quickly and efficiently. The time and expense of tracking down personnel who had worked on the design and manufacture of the equipment was eliminated. In this scenario, NASA personnel followed the same systems engineering processes that they currently do, but with the addition of a robust, reliable end-to-end virtual model, which significantly reduced the time and resources required for problem troubleshooting.

V. Conclusion

NASA is at a crossroads in the types of missions it will perform as a result of the retirement of the Space Shuttle and the extension of the International Space Station's operational life. The Engineering Directorate at Marshall Space Flight Center has made a significant commitment to managing product data at each stage of the lifecycle to help ensure the rigor and accuracy of engineering data, especially transitions from the as-designed to the as-built and as-flown configurations. Investments made in this institutional capability have benefitted the technical user community, as well as the systems management aspect of technology and space system design, development, testing, and evaluation.

Because NASA's systems engineering processes and tenets are already closely aligned with the PLM methodology, the synergy between the two is natural, and adopting PLM as an adjunct to the existing systems engineering efforts can promote a greater emphasis on data sharing and integrity throughout the product lifecycle, ensuring that the products that result from milestone reviews and key decision points are shared effectively throughout the organization.

While NASA has taken steps to evolve its systems engineering competency to meet the demands that come from designing more complex technologies, this alone is not enough to push the state of the art. Adopting a methodology such as PLM can ultimately link the execution of the NASA systems engineering processes and the management of authoritative engineering data to reduce risk and increase the probability of mission success.

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Abstract

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Sustainable space exploration solutions demand that all lifecycle phases be optimized. Adopting PLM, which has been used by the automotive industry for many years, for aerospace applications provides a foundation for strong, disciplined systems engineering and accountable return on investment by making lifecycle considerations variables in an iterative decision-making process. This paper combines the perspectives of the founding father of PLM, along with the experience of Engineering leaders who are implementing these processes and practices real-time. As the nation moves from an industrial-based society to one where information is a valued commodity, future NASA programs and projects will benefit from the experience being gained today for the exploration missions of tomorrow.