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Lean Product Development Flow

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ABSTRACT

A general holistic framework, also called a process—named “Lean Product Development Flow (LPDF)”—for organizing the engineering work of Product Development (PD), has been proposed as a contribution to the emerging field of Lean Systems Engineering. The framework is based on Lean Principles, with emphasis on PD value-pulling workflow pulsed by takt periods. The value is defined as (1) mission assurance/product quality, (the traditional goals of Systems Engineering) and (2) reduced program cost and schedule achieved by a radical reduction of waste. LPDF is recommended for smaller design programs based on a high degree of legacy knowledge, with technologies mature enough so that the program feasibility is not in question. LPDF may involve limited-scope research, provided that it can be identified early in the program, and carried out separate from the main workflow. The paper is focused on aerospace and defense programs, which are presently burdened with as much as 60–90% of waste, but the process is also applicable to commercial programs. LPDF can be applied to the entire PD, to one or more milestones, and to a multilevel program. LPDF requires both detailed preparations and disciplined execution. The preparations include detailed Value Stream Mapping, separation of research from the main workflow, parsing of the Value Stream map into Takt Periods, architecting the LPDF team using dynamic allocation of resources, and team training. LPDF execution is organized as a flow through a series of short and equal work Takt Periods, each followed by an Integrative Event for structured, comprehensive coordination. Strategic and flexible tactical mitigations of uncertainties must be applied during the flow. LPDF also requires excellent leadership of a Chief Engineer, modeled after Toyota and Honda, who is a dedicated program “owner,” an expert systems designer, a strong leader focused on the program and product integrity, and skilled in consensus-building. The Chief Engineer is responsible for the entire program, with Assistant Chiefs assisting in selected technical areas, and a Project Manager assisting with program administration. An industrial pilot program is currently being undertaken to validate the method. © 2004 Wiley Periodicals, Inc. Syst Eng 7: 352–376, 2004

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Key words: lean; lean product development; value; value-based; lean systems engineering; flow; takt time; takt period; value stream mapping; pull; chief engineer; heavyweight program manager; design; legacy; uncertainties

1. INTRODUCTION

The paper presents a general holistic framework (also referred to as a process)—named "Lean Product Development Flow (LPDF)"—for organizing the effort of technological Product Development (PD). It addresses the national need for improving productivity and quality of design, engineering, and manufacturing processes in aeronautical industry [Murman et al., 2001; Murman, Walton, and Rebentisch, 2004]. During the 1990s, the focus on productivity and quality was captured by the popular mantra "better, faster, cheaper" first promoted at NASA and soon adopted by the defense establishment [Murman et al., 2001]. Regrettably, a number of failures of major space systems have occurred during that same period. Subsequent investigations, summarized in T. Young [2000], blamed the failures on excessive focus on cost reductions at the expense of mission assurance, neglecting to apply important Systems Engineering practices. In other words, the problem was that the "cheaper and faster" was tried at the expense of the "better." A saying made rounds in the industry that "it is possible to have any two of the three in 'faster, better, cheaper,' but not all three simultaneously." The failures gave an anecdotal bad name to the "faster, better, cheaper."

This paper takes a strong position that all three must be pursued to satisfy the national need for affordable and rapid acquisition of complex space systems, and that all three are imminently achievable due to the huge untapped productivity reserve hidden in the PD waste (defined as activities that do not add value to the product). Both industry and government must strive to continually and simultaneously improve all three: "better" quality, in the form of mission assurance, "faster" for space program and national security effectiveness, and "cheaper" for national affordability.

The LPDF is based on the same powerful five Lean Principles which organized production work as an uninterrupted flow proceeding through all processes at a steady pace without rework, backflow, or inventories, yielding extraordinary benefits in productivity [Womack, Jones, and Roos, 1990; Womack and Jones, 1998]. The ultimate intent of the proposed LPDF is to reproduce this success in limited Product Development work. Specifically, the intent is to radically shorten the overall PD schedule and cost by an aggressive reduction of the all-pervading PD waste, without sacrificing the value, as defined by all the traditional quality goals of Systems Engineering (SE) [INCOSE, 2004],[1] such as: mission assurance, product integrity, life cycle performance, first-time quality, safety, functionality, redundancy, robustness, durability, flexibility, maintainability, sustainability, support, and any other characteristic specified by the customer.[2] In order to achieve these ambitious goals, the Lean Principles are interpreted as a set of recommendations for detailed PD program preparations; disciplined, comprehensive and flexible execution; and consummate leadership.

LPDF is proposed as a contribution to the emerging field of Lean Systems Engineering, defined as Systems Engineering focused simultaneously on value creation and waste elimination [Murman, 2002].

LPDF is recommended for a limited class of developmental programs, as follows.

Applicability of LPDF. Technological Product Development (PD) is a broad term that includes all conceivable tasks involved in the design of technology-based objects or missions which provide value to the product stakeholders, both defense and commercial, hugely varying in scope, complexity, degree of integration, multidisciplinary character, and the availability of legacy knowledge. Arguably with fuzzy boundaries, complex technological programs can be loosely classified into the four broad classes of systems described in Box 1 in the order of decreasing complexity, duration, and budgets.

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[1] The INCOSE web site contains the following definition: "Systems Engineering is an interdisciplinary approach and means to enable the realization of successful systems. It focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, then proceeding with design synthesis and system validation while considering the complete problem: Operations, Performance, Test, Manufacturing, Cost & Schedule, Training & Support, Disposal. Systems Engineering integrates all the disciplines and specialty groups into a team effort forming a structured development process that proceeds from concept to production to operation. Systems Engineering considers both the business and the technical needs of all customers with the goal of providing a quality product that meets the user needs."

[2] SE quality is often described as the proper utilization of all the SE processes required to create the PD quality, such as systems architecture, risk management, requirements flow down, validation and verification, system flow down and integration; engineering design, including Design for Manufacturing and Assembly (DfMA), Design for Testing (DfT), Design for Support; etc.

CLASSIFICATION OF TECHNOLOGICAL PD PROGRAMS

A. "CLIOS" Systems. The largest PD programs, described in the emerging field of Engineering Systems as Complex, Large, Integrated, Open Systems [Sussman and Dodder, 2003], involve and impact the environment, public policy, and social aspects in addition to technology. Their defining feature is that they exceed the bounds of traditional Systems Engineering, and engineering design and sciences. Examples: national telecommunications network, Internet, China's Three Gorges Dam, and Mexico City's transportation/environmental system. Each CLIOS system requires extensive research and development. Practical tools for developing CLIOS programs in an integrated fashion are still in infancy [Moses, 2004; Allen, 2004; Hastings, 2004; Rhodes and Hastings, 2004]. These programs are too complex for LPDF.

B. Complex Frontier Systems. This class involves the complex integrated developmental programs, typically seen in space and defense applications, challenging the frontiers of knowledge, lasting from a few to 10 or more years, involving up to thousands of participants, typically spanning many large private and governmental institutions, with large supply chains that are national or even international in scope, involving significant "unknown" uncertainties, and requiring comprehensive fundamental research and development. Typically, they require the "system of systems" approach. The Apollo program, the original Space Shuttle design, the ongoing Missile Defense system, or the future Human Flight to Mars, are examples of the largest of these programs. The smaller programs in this range might include the design of a new type of space vehicle, spacecraft platform, aircraft, or weapon system. Although these programs almost always challenge and stretch the boundaries of both Systems Engineering and engineering sciences, they can be successfully developed essentially within these expanding disciplines. Total Technology Development [Schulz et al., 2000] has been proposed as a comprehensive method for structured management of these programs.[3] An important feature of the long-lasting programs is that they are likely to experience technology changes in midstream. Therefore, they need a development process that inherently embraces flexibility to accommodate such changes [Iansiti and MacCormack, 1997]. These programs involve too many instabilities and big uncertainties to benefit from LPDF.

C. Complex Legacy-Based Systems. These are smaller developmental programs typically lasting less than 2 years and involving up to several hundred participants. Much of the knowledge is based on legacy programs and mature technologies, which makes them relatively predictable and stable, without the need for significant schedule-delaying research. Research effort can be acceptable as a part of the PD only if the need for it can be identified during the program detailed planning phase, and the effort can be placed on a parallel track, separate from the main work flow, to be handled by a separate team, and staffed and scheduled so as to provide the results when needed without delaying the main program work flow. It is assumed that the other "routine" uncertainties involved in these programs can be mitigated using good engineering and leadership practices. The risk of major product or process technology changes disrupting the schedule during the short program duration is small. The programs can be well managed within the fields of Systems Engineering, engineering design and sciences, and supportive administration. Example of a suitable program: the design of a communications satellite based on a formerly developed platform and architecture with many subsystems adopted directly or only slightly modified from the legacy spacecraft, and with perhaps a more powerful payload and supporting subsystems, e.g., larger power, batteries, antennas, and bus. Such a program may still face taxing uncertainties and technical challenges of meeting the margins, as well as production, assembly, and integration issues. However, the program feasibility should not be in question. The program may still involve the "system of systems" issues of integrating, for example, the spacecraft system, launch system, ground support system, as well as their subsystems. Most of these issues should be solvable using good engineering practices and the knowledge and experience of similar former products. The programs employ mostly engineers, technicians, and administrators in supporting roles. Major suppliers who contribute to the PD would be staffed similarly. Thus, most of the program cost is engineering and business labor. This is an important observation indicating that the PD cost reduction should be roughly linear with the PD time reduction, according to the adage that "time is money."

D. Commercial and Defense Programs Smaller and/or Simpler than (C).

Box 1. Classification of Technological PD Programs

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[3] The paper presents a four-phase general framework for developing total technology, characterized by superiority, robustness, maturity and flexibility. The phases include: (1) Integrated Technology Strategy; (2) concept generation, analysis, enhancement, evaluation and selection; (3) robustness development and analysis; and (4) technology selection, transfer and integration.

LPDF is recommended for the program classes (C) and (D), or to small fragments of programs (A) and (B) which can be defined well enough to be equivalent to class (C). LPDF can also be applied to a segment(s) of a PD, and to a multi-level PD program. These cases are discussed in the text.

Within these limitations, the PD effort is defined simply as the engineering development of knowledge about the product, or as a process of eliminating the uncertainty about the product [Browning, 2002]. The PD work begins with the product or mission value proposition, typically captured in a proposal or a contract, including stakeholder identification. The PD is completed when the design is ready for error-free production, that is, when the manufacturing stakeholders are ready to accept the design knowing precisely what to build, how to build it, and what effort and business structure are required to build each part and the entire system.

The focus of this paper is to make the LPDF organization of work as efficient as possible without taking anything away from the program quality goals, by tapping the huge productivity reserve hidden in the PD waste, as discussed next.

Waste. Waste is defined as anything other than the minimum required for mission assurance. Even within the relatively mature class (C) of modern aerospace and defense products, PD suffers from a schizophrenic dichotomy: It involves at the same time the most advanced products and engineering processes ever invented by man, and the design process itself which manifests one of the least efficient organizations of engineering effort ever practiced. The amount of waste in aerospace and defense PD programs is estimated at 60–90% of the charged time, with about 60% of all tasks being idle at any given time [Cool, 2003; Browning, 1998, 2001; Chase, 2001; Joglekar and Whitney, 2000; McManus, 2004; Millard, 2001; M. Young, 2000]. According to these authors, while the estimates lack the scholarly rigor, they are consistent enough, across corporations, programs and years, to yield a comfortable level of confidence. It is also common knowledge that the aerospace programs of the last decades have suffered from notorious budget and schedule overruns. The focus of this paper is on aerospace and defense programs precisely because they offer the biggest opportunities for improvement from LPDF. But the process can also be used for commercial programs. LPDF success depends on the ability to identify and reduce, if not eliminate, the waste in PD. Box 2 contains a summary of the current knowledge about PD waste, presented in four parts. The first part summarizes the classical categorization of work activities into value-added (VA), non-value-added (NVA, pure waste), and

WASTE CLASSIFICATIONS
VA, NVA, and RNVA

Womack and Jones [1998] classified all product-making activities into value adding (VA), to be continually perfected; non-value-adding (NVA), to be eliminated; and required non-value adding (RNVA), such as those required by contract or law. No formal study is available on the relative amounts of NVA and RNVA in aerospace programs, to the author's knowledge, and their demarcation is vague [McManus, 2004].[4] Even though the current governmental acquisition policies tend to allow contractors increasingly more leeway in program execution, [McDaniel, 2004], with potential to reduce RNVA activities, at the time of this writing, the amount of the RNVA mandated by contracts and promoting corporate bureaucracy remains considerable imposing overwhelming administrative burden on programs.

Self-evident NVA activities alone constitute a huge waste. NVA is also often hidden within larger, apparently VA, activities and shows up only upon detailed decomposition of the latter. Example (observed by the author): A moderately advanced thermal analysis of an avionics subsystem (an apparently VA activity) took 10 weeks: 5 weeks of NVA wasted by the analyst chasing the needed input data, which was not provided to him on time or in the usable format because of poor program planning, coordination, and communication. Once the analyst had the data in hand, he completed the VA work, including modeling, analysis, and a

[4] McManus [2004 p. 109] quotes Browning as follows: "Whenever a group attempts to classify PD activities as one of Womack and Jones' three types, it typically experiences some passionate debate. PD activities can be difficult to classify, and no one wants to see their activity branded as 'waste,' necessary or not. Actually, most of the NVA elements are buried deep inside VA activities. In the largest sense, the overall PD process adds value (a VA activity). Yet, decompose it and NVA and RNVA activities appear within. Continue to decompose the VA activities, and activities of the other two types continue to appear. Decompose *ad infinitum*, and the only thing left adding value (by the 'three types' definition) is the final output materializing out of thin air! Thus, debating [the activity type] is not very helpful in practice.… Just think of the entire process in economic terms: remove NVA activities and make everything else as productive and efficient as possible. The concept of 'necessary waste' can be an unnecessary distraction."

report, in 1 week. Then, 4 weeks were wasted on complex approval and dissemination protocols of which one week could be blamed on the contract (RNVA) and 3 weeks were wasted on multiple approvals, handoffs, and general bureaucracy (NVA). Throughout the task, stressful pressure was applied on the analyst "to finally deliver the results," which represents a significant if rarely considered indirect waste. Such work environment is a reason why talented engineers decreasingly regard work in defense industry as enjoyable. This example also demonstrates that "pinching" the VA processes (in this case, trying to shorten the week-long analysis) without addressing the huge NVA that occurs between the VA processes is ineffective. Indeed, while VA processes should be continually improved, the main benefit comes from eliminating the waste, both NVA and RNVA, between the VA processes. In this example, better planning, more frequent coordination, and tighter leadership should be conducive to a significant reduction of the waste without sacrificing any of the analysis quality.

MILLARD'S SEVEN CATEGORIES OF WASTE

Millard [2001] classified PD waste into the seven categories used for manufacturing:

(1) Overproduction (creating unnecessary information)
(2) Inventory (keeping more information than needed)
(3) Transportation (inefficient transmittal of information)
(4) Unnecessary movement (people having to move to gain or access information)
(5) Waiting (for information, data, inputs, approvals, releases, etc.)
(6) Defects (insufficient quality of information, requiring rework)
(7) Overprocessing (working more than necessary to produce the outcome)

MORGAN'S 11 CATEGORIES OF WASTE

Morgan [2002] classified PD waste into 11 categories:

(1) Hand off (transfer of process between parties)
(2) External quality enforcement (including performance requirements)
(3) Waiting
(4) Transaction waste
(5) Re-invention waste
(6) Lack of system discipline
(7) High process an arrival variation
(8) System overutilization and expediting
(9) Ineffective communication
(10) Large batch sizes
(11) Unsynchronized concurrent processes

SELECTED COMMON-KNOWLEDGE REASONS FOR WASTE

- Weak planning and leadership of PD programs, lip-service Systems Engineering, ad-hoc management
- Lack of frequent and comprehensive coordination, and poor communications among team members, particularly across departments, divisions, and supplier nodes
- Starting each program anew without utilizing the legacy knowledge, and not learning from past mistakes
- Inefficient, fragmented, multipoint, multiperson, multiformat approvals, and release protocols
- Excessive conservatism, bureaucracy, compartmentalization, corporate structure of "stovepipe silos"
- Nonoptimal use of human resources, e.g., expensive engineers asked to perform RNVA or NVA
- Traditional focus on point designs, lack of exploring set designs, poorly managed schedule-busting iterations, elevation of trivial uncertainties to the status of R&D
- Using obsolete 2D drawings instead of a single-point-release database with 3D data, selectively accessible
- Push rather than pull-based specifications and requirements.

Box 2. Summary of PD Waste

required non-value-added (RNVA, non-value-added but required by, e.g., law or contract) [Womack, 1998]. A typical example is included. The second part lists the PD waste classification into the same seven categories that are used in Lean for manufacturing waste [Millard, 2001]. The third part presents a more comprehensive classification proposed by Morgan [2002]. Finally, Box 2 lists selected common-wisdom reasons for the waste, which do not appear to map directly onto the three classifications, suggesting an opportunity for further research about the PD waste.

The complex historical reasons for the waste are beyond the scope of this paper. Bad governmental acquisition practices, inadequate incentives for cost reductions, historical program complexity increasing faster than the knowledge of program management, and various social and political pressures can be mentioned as partial reasons. However, a working hypothesis of this paper is that the root cause for most of the waste is that PD engineering and management have never left the craft organization of work. Craft is characterized by the lack of flow and pull, often ad hoc planning and execution, and large variability in work content, sequencing, duration, effort, outcome, and cost, all well-known symptoms of PD programs. In production, Lean confronted craft with extraordinary success. LPDF attempts to confront the PD craft with Lean, too.

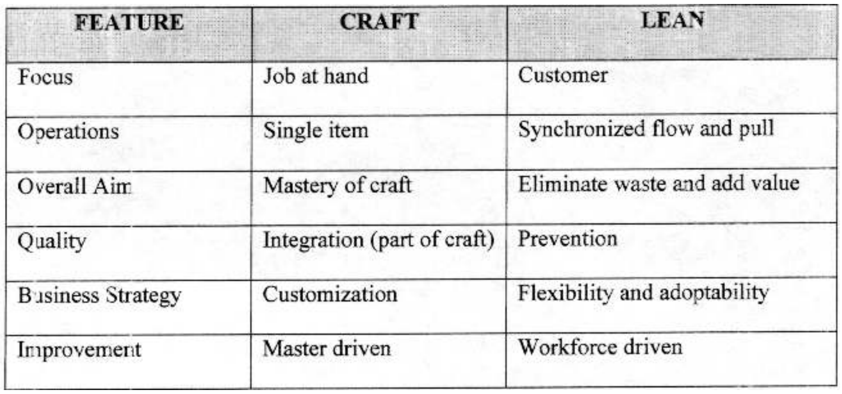
From Craft to Lean. The field of production has seen two major revolutions during the last century. The first was the invention of a moving assembly line by Henry Ford. The moving line was made possible by splitting and balancing the work among the sequential processes and implementing a common pace for all processes. The key to success was the ability to split the complex craftwork into separate tasks of short and equal duration. The model-T moving line cut the former craft-based production cost and throughput time tenfold, with the corresponding vast increase in Ford's profits. "Lean Production" was the second revolution. It was an elegant generalization of the Just-in-Time and Toyota Production Systems by [Womack, 1998], who formulated the method in terms of five following Lean Principles:

1. Define value to the program stakeholders
2. Plan the value-adding stream of work activities from raw materials until the product delivery while eliminating waste
3. Organize the value stream as an uninterrupted flow of work pulsed by the rhythm of takt time, and proceeding without rework or backflow
4. Organize the pull of the work-in-progress as needed and when needed by all receiving workstations
5. Pursue "perfection," i.e., the process of never ending improvements

Lean production added the benefits of a tenfold cut in inventory and floor space, and vast improvements in product quality and work morale. Lean shifted the craft paradigm in a number of other important characteristics, as listed in Table I adopted from Murman [2002].

The proposed LPDF framework adopts the concepts of both the moving line (flow of work pulsed by takt time) and Lean Production (pulled deliverables, focus on delivering maximum value with minimum waste) to PD, attempting radical cuts in both program cost and schedule, even though no direct data are yet available to validate the cuts quantitatively.[5] At the time of this

Table I. Contrasting Craft Work and Lean Work



FEATURE	CRAFT	LEAN
Focus	Job at hand	Customer
Operations	Single item	Synchronized flow and pull
Overall Aim	Mastery of craft	Eliminate waste and add value
Quality	Integration (part of craft)	Prevention
Business Strategy	Customization	Flexibility and adoptability
Improvement	Master driven	Workforce driven

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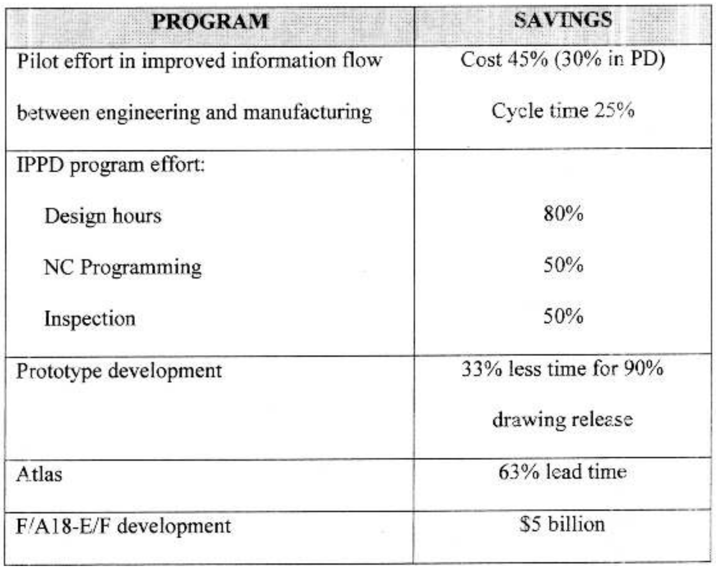
[5] It is doubtful whether Henry Ford had rigorous data available while setting up his moving line.

Table II. LAI Lean PD Successes, [Murman, 2004]



PROGRAM	SAVINGS
Pilot effort in improved information flow between engineering and manufacturing	Cost 45% (30% in PD) Cycle time 25%
IPPD program effort:	
Design hours	80%
NC Programming	50%
Inspection	50%
Prototype development	33% less time for 90% drawing release
Atlas	63% lead time
F/A18-E/F development	$5 billion

writing, the method is being tested in a 2-year pilot program (see Section 4). Results should be available for publication as a companion paper within 2 years. Until then, the LPDF process is offered as a proposal. However, limited circumstantial data from other Lean projects suggest a significant potential of Lean in PD. Table II lists a sample of Lean projects with a substantial PD content, attempted by various members of the Lean Aerospace Initiative consortium [LAI, 2004], and the resultant savings. As Table II indicates, the savings in cost and time varied from 25% to 80%. Since LPDF simultaneously tackles more Lean aspects than any of the quoted projects, its potential for cost and time reductions should also be significant.

2. LEAN PRODUCTION

This section presents a review of relevant features of the hugely successful Lean Production. In manufacturing, the term "takt time" denotes the rate at which completed products leave the production line for delivery to the customers. It is equal to the amount of time allocated to each workstation on the line for the robust completion of its task. Each worker or process must work to the common takt time; otherwise pileups or gaps occur before and after the offending workstation. As customer orders increase, the production rate must be increased and the takt time reduced. This is accomplished by adding resources—up to the capacity of the system—rather than by forcing processes to run faster. Flexibility in adding and removing human and machine resources is an important factor in profitability. The term "flow" denotes the uninterrupted motion of work pieces at a steady pulse of takt time through all processes of the line with no backflow or rework. "Pull" is the concept of each process "pulling" the incoming work from the upstream process when needed and in the amount needed. Pull is the opposite of push where the creator pushes his work output without regard for the need of the receiving station. Kanban is a signal from the receiving station to the supplying process about the readiness for the next part or work in progress. Kanban signals can be as simple as a hand wave or an empty bin placed for pickup, to more complex electronic signals, or small mini-max supermarket-type batches.

Making complex production flow according to the takt pulses is difficult. The implementation requires carefully splitting and balancing the total work among the workers, perfecting each process, and providing each worker with adequate parts, tools, training, and ergonomics to make timely and robust completion of the task possible. **The key to success, which is also the key to the present method, is the ability to plan and parse the total work into tasks of equal duration, and small enough that each task becomes predictable in terms of outcome, quality, effort, and cycle time.** Numerous references describe this production system, [e.g., Spear, 1999]. Lean Production is the most efficient method known for flexible delivery of quality products in the shortest possible time and at minimum cost. Toyota is recognized for both the original and the best implementation of the system, which has been perfected to the unmatched level of being able to assemble eight different car models in any mix on the same moving line [Toyota, 2003].

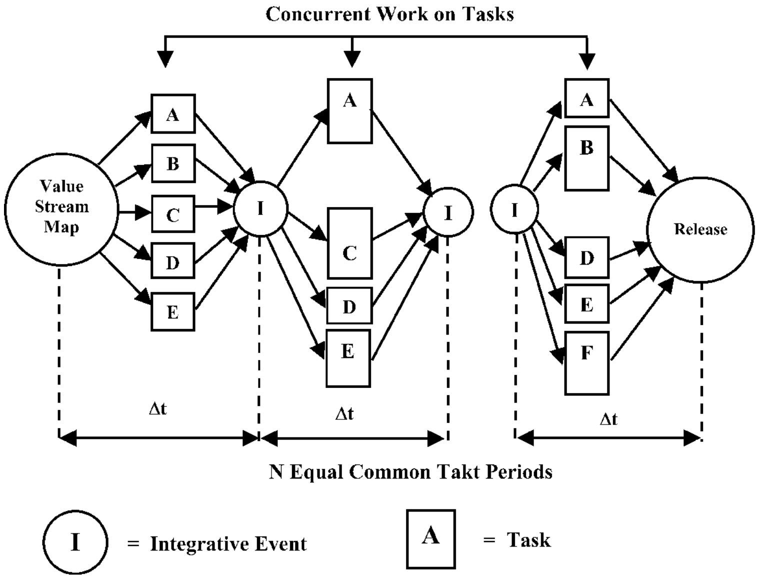


Figure 1. Schematics of Lean Product Development Flow.

3. PROPOSED LEAN PD FLOW

Overview. The proposed method is named Lean Product Development Flow (LPDF). Figure 1 schematically illustrates the flow as an idealized timeline. The effort begins with the value definition and detailed planning captured in a Value Stream Map. The flow ends with the release of the deliverables. Between the two ends, the flow proceeds at a steady rate, as on a moving line, as follows. The flow consists of a sequence of a large number (e.g., 50–100) of equal "homework" periods called Takt Periods, each terminating in an Integrative Event. The Takt Periods are of *equal and short durations* (e.g., 1 week). Their role is to provide a constant, common, and frequent rhythm to the entire team. Within each Period, work is coordinated by the Core Team and executed by any suitable architecture of concurrent and synchronized teams, part-time employees who are dynamically allocated from their functional departments, and individuals, all assigned as needed to assure the timely completion of the work within the given Period. The number of individuals assigned to different Takt Periods varies depending on the effort assigned to the Periods. Thus, all Takt Periods are of equal duration, with common deadlines, but not necessarily equal effort or team composition. The PD team follows a number of important enabling practices to make the program a success, including high-fidelity planning during the Value Stream Mapping, pursuit of excellence in the execution of the flow, tight leadership and management, and good strategic and tactical mitigation of uncertainties. All team members receive training in the LPDF principles, effective and seamless unstructured communications during the Takt Periods, and a highly structured coordination during the frequent Integrative Events. Detailed descriptions of these features follow the order of the five Lean Principles. The discussion of each Principle ends with a text Box summarizing the success factors and metrics, if applicable, proposed for the given Principle.

LEAN PRINCIPLE 1: DEFINE VALUE

The value of LPDF is defined as delivering:

I. A robust product (design) satisfying stakeholders' functional and contractual requirements and expectations (which is the traditional role of Systems Engineering), including all quality aspects and features required for mission assurance.
II. Delivering item I within short schedule and at minimum cost, by removing PD waste.

The present framework deals directly with item II; however, it is conducive to improving I, as well as raising the enjoyment of work due to the inherent elimination of the frustrations associated with PD waste.

Holistically, the LPDF effort must begin by precisely defining the final deliverables of the design (or its milestone), which will assure the value proposition. The typical value proposition for PD is the subsequent ability to perform error-free and cost-effective production of the product satisfying the needs of the customer.

SUCCESS FACTORS	SUCCESS METRICS
1. Identification of LPDF stakeholders 2. Formulation of value deliverables, which is acceptable to the stakeholders	Amount of LPDF throughput time cut relative to the competition and to the earlier similar programs or non-LPDF estimates

Box 3. Success Factors and Metrics for Lean Principle 1

Thus, the users (the end customer and the manufacturing stakeholders) should pull the deliverable definition. The identification and definition of stakeholders and their different needs is usually quite complex in defense and aerospace programs. For example, the paying end customer for a military aircraft (the government) is not the same as the end user (military pilots and mechanics). Comprehensive discussions of the value proposition are offered in [Stanke and Murman, 2002] and [Browning, 2001].[6]

LPDF Throughput Time. The total LPDF time ("throughput" time) is a critically important part of the value proposition, yet in practice it is an arbitrary aspect of PD. The time should be decided at the beginning of the Value Stream Mapping effort, for the same reason as on a moving line. Ideally, the throughput should reflect the time when the customer needs the product, or the time needed to beat the competition, rather than the schedule convenient for the contractor. In the absence of a customer-set deadline, the following factors are normally considered when choosing the schedule.[7] Program cost, competitive reasons, and fast changes of technology strongly favor shorter schedules. Cash flow, leveling of simultaneous programs in the company, and employment stability favor more tranquil schedules. In industrial practice, these factors are rarely studied quantitatively, and the schedule selection tends to be somewhat arbitrary.[8] A radical step is recommended here to reduce the traditional legacy-based (or proposal-quoted) throughput time by the fraction of the PD waste that the program management is ready to tackle. For example, if the management estimates that 20% of the time wasted on a recent similar program was self-evident and would be feasible to eliminate, the throughput time should be cut by that fraction. Ambitious leadership might favor more aggressive cuts.[9] The risk of the schedule cutting is small: that, of the schedule slipping back towards the traditional asymptote.[10] In the spirit of continuous improvement, larger cuts should be possible as experience with the LPDF process increases. Admittedly, this is a radical and arbitrary approach, however, not less arbitrary than the practice of cutting 25–50% of the schedule because padding is suspected. Box 3 lists the success factors and simple metrics recommended for Lean Principle 1.

LEAN PRINCIPLE 2: DEFINE VALUE STREAM

Common wisdom calls for "good planning" at the beginning of PD programs. Experience-based, competition-motivated, consensus-created optimized Value Stream Mapping (VSM) parsed into short Takt Periods is the ultimate good plan. The VS must be mapped before the flow can begin. While subsequent execution permits flexible adjustments of the Tasks in real time, the adjustments should be used as a tactical mitigation of uncertainties, rather than a poor substitute for good initial planning. The VSM lists all the activities that create value, starting with "raw materials" and ending with value deliverables. The map combines a process map with data about how the process works, indicating the effort and cycle time data. The VSM is a comprehensive planning period, which may take 5–20% of the PD schedule, depending on the team experience and program complexity.

In production applications VS mapping is well understood at this time [Rother and Shook, 1999]. It involves two milestones called Current State map and Future State map. The former is an image of the current

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[6] Browning [2001, p. 169] argues for more focus on value and less on waste elimination in PD programs, paraphrasing: "Liposuction will slim a person, but will not make him win races; good exercise will."

[7] The considerations are limited to fixed-price contracts or own-cost programs, because "cost-plus" programs have different priorities and constraints.

[8] A humorous aspect of PD scheduling is that proposal managers not infrequently collect estimates of cycle time from departments, add them up, and then arbitrarily reduce them by a big fraction, such as 25–50%, suspecting that the estimates were padded.

[9] After 5 years of experimenting, Henry Ford realized a 90% throughput reduction from his assembly line, although it is doubtful that he could predict it *a priori*.

[10] The author's subjective experience indicates that the initial cut of 30% on a 1-year satellite program should be realistic, based on the anecdotal estimates of waste reduction opportunities.

practices, and is the basis for subsequent elimination of waste. The Future State map defines the work flow after the elimination of the identified waste.

In PD, VS mapping appears less understood and practiced. Morgan [2002] presents a comprehensive example of the Toyota process for developing car bodies with considerations of Queuing Theory and Lean.[11] At the time of this writing, an important tool called the Product Development VSM Manual is about to be released [McManus, 2004]. It presents easy-to-follow step-by-step guidance for developing Value Stream Map starting with the Current State map, proceeding through the identification and elimination of PD waste, and ending with the idealized Future State map. The text includes an in-depth discussion of PD waste and mitigation techniques. Intended for practitioners, it includes numerous explanations and examples. Hopefully the manual will popularize the use of PD VSM in industry.

Value Stream mapping of LPDF consists of the five following steps:

a. Selection of Takt Period
b. Current State Mapping
c. Future State Mapping
d. The parsing of the Future State Map into Takt Periods
e. Designing the LPDF team

These steps are discussed in turn.

Selection of Takt Period. LPDF requires that the work be parsed into equal and short Takt Periods. The first step is to select the Takt Period for the flow. This requirement contravenes the current universal engineering practice of executing large, functional tasks, such as modal analysis of a structure, as a continuous effort. This traditional habit should not be difficult to change with good training and leadership. LPDF is a more disciplined version of the work parsed into packets of work, proposed by [Goldratt, 1997]. Five arguments favor the parsing of longer tasks, as follows[12]:

a. The length of time between Integrative Events is analogous to the batch size in Production. Lean demands driving the batch size to a minimum. In PD, minimizing the Takt Periods minimizes the time wasted to the discovery of a defect and facilitates an urgent corrective action before the problem grows uncontrollably.
b. The mathematical model of Yassine, et al. [2003] analyzes the information "churning" defined as the instability in PD knowledge manifesting itself as a series of patterns, each apparently first converging to a solution, followed by an unexpected divergence (instability). The authors demonstrate that the churning is caused by the PD information effectively hiding between reviews, and conclude that minimizing the time interval between reviews can minimize the churn. The churn is illustrated by the example of an inefficient drawing release process (a well-known problem in industry): A manager has released a new version of a drawing, but the notification about this fact has not yet been transmitted to the users-analysts, who unknowingly continue using an obsolete drawing until the next staff meeting. The PD convergence (new drawing) is followed by the solution instability (working off an obsolete drawing), caused by the information about the new drawing "hiding" until the next meeting.
c. Using a simple mathematical model, Ha and Porteus [1995] calculate the optimum frequency of reviews as a function of the review setup time, defined as the effort necessary to prepare for each review. The model indicates that if the setup time is negligible, the reviews should be as frequent as possible. Frequent and regularly scheduled Integrative Events are close to this condition: No effort is needed to schedule the meetings by definition, because all team members know the regular meeting times, e.g., Friday 8 AM. Some minimum setup is required to prepare for the Integrative Events: organizing thoughts, summarizing results and trade-offs for decisions, bringing issues to the attention of the team, etc.; but this effort can be efficiently handled in at most a few hours, on the afternoon before the day of the Integrative Event, and not all team members need to do it every time, as indicated by [Sobek, Liker, and Ward, 1998] describing the Toyota model.
d. Morgan [2002] and Browning [1999] present persuasive arguments for blaming much of the PD waste on the lack of frequent and comprehensive coordination.
e. High variability in task sequencing, effort, timing, and quality, characteristic of craft, is destructive to product quality and schedule. The lesson of pulsed production lines indicates that shorten-

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[11] Besides being a study of PD VSM, the author makes several recommendations consistent the LPDF process, including: the need for very early detailed task scheduling and discipline, creating flow, focus on best practices, minimizing batches, and pull.

[12] Contrary to the thesis of this paper, Toyota PD system, which demonstrated the precedent setting reduction of new car development time from 48 months to 18 month in about 10 years, tends to hold few Integrative Events at long and uneven time intervals [Ward et al., 1995; Sobek, Liker, and Ward, 1998]. This particular feature of Toyota PD is not recommended in isolation from of all other integrated and perfected Toyota PD features, for which the aerospace and defense industry does not seem to be ready at this time.

ing Takt Period makes tasks simpler and more consistent. In engineering, large complex tasks inherently have the character of craft, that is, they are highly prone to the large variability. Contrary to the engineering tradition, most tasks can be parsed into short subtasks. For example, an experienced dynamics engineer should have no problem parsing a modal analysis as follows: gathering the task requirements and accessing the structure drawings or 3D model; studying the drawings; constructing finite element models of individual parts, joining the parts into the integrated structure model; entering material properties and other run parameters; executing modal analysis; plotting the modes; analyzing the results; and writing a short report. These subtasks are so routine that a competent engineer should be able to estimate their duration and level of effort very accurately, with minimum padding. The engineer should also be able to identify accurately all required major inputs and outputs for each subtask. This "splitting" principle should be used for the vast majority of the tasks. There may be exceptions to the parsing, e.g., a test involving a continuous temperature cycling, or a chemical treatment, lasting longer than 1 Takt Period. This exception type must be permissible as a rare well-justified event, provided that the extended task has predictable outcomes, cost, completion time, and effort, and can be logically aligned with the common Takt Period for reporting purposes, e.g., the ability to report that "In Takt Period No. 17 the test is 35% completed, as scheduled."

In conclusion, very short Takt Periods are recommended. It is judged that LPDF lasting up to 2 years should adopt the Takt Period of 1 week, with work performed, say, Monday to Thursday, and the Integrative Events held on Fridays. Weekly rhythm is splendidly natural in that it matches the employee rhythm of work, rest, and family life. Routine, well-defined, well-progressing programs experiencing few integration issues can practice longer Takt Periods.

Program Room. Even in moderate-size programs both Current and Future State maps are complex drawings, so a large room with ample wall space (called the Program Room, or colloquially the "War Room") should be dedicated to the program for the entire duration [Smith, 1998]. The VSM effort, all Integrative Events, and ad hoc meetings should be conducted in the Room, with the VSM and program notes conveniently in view. The Takt Periods should be delineated on the walls by vertical marks, for the entire LPDF duration, for posting of the Task sheets. Each Task sheet should fit into a letter-size page or smaller; thus the vertical lines should be spaced by 1 foot (requiring a Room with 52 feet of clear circumference for a 1-year program). Figure 2 illustrates the proposed organization of a wall in the War Room. The wall layout is preferred to an electronic implementation, because it enables the Core Team members to read all tasks, brainstorm, and negotiate in real time the task parsing, precedence, concurrency, synchronicity, scope and effort, inputs and outputs, and waste, to finally reach a consensus. Ideally, a few smaller rooms should be available nearby for breakaway discussions. The offices of the Chief Engineer and Program Manager and their staffs should be located in close proximity. The room should contain networked computers, printers, projectors, ample writing materials, and a large conference table with enough chairs to accommodate the Core Team.

WEEK	1	2	3	4	5	6	7	8	etc.	25	26	27	28
TASKS	☐ ☐ ☐ ☐ ☐	☐ ☐ ☐ ☐	☐ ☐ ☐ ☐	☐ ☐ ☐ ☐ ☐	☐ ☐ ☐	☐ ☐ ☐ ☐	☐ ☐	☐ ☐ ☐ ☐ ☐		☐ ☐ ☐	☐ ☐ ☐ ☐ ☐	☐ ☐ ☐ ☐	☐ ☐ ☐
NOTES													

Figure 2. Sample wall in the War Room.

Mapping the Current State. The Current State map is a detailed graphical representation of the present PD process, showing all tasks, their precedence, and control points, and is a starting point for subsequent identification of waste. The final Value Stream Map used on the most recent legacy program(s) is an efficient way to begin the Current map. The knowledge of a legacy program, its problems, solutions, technical approaches, etc., is equivalent to raw materials in production.[13] Good corporate memory is invaluable in this step. Incentives should be introduced to collect and preserve the value stream maps from past programs (as well as system and component performance charts, system-level tradeoff charts, nondimensional ratios, architectural properties, and numerous other useful design data). Starting with the legacy knowledge is helpful even if only partial information is available, such as the process map of an actually executed program, or the

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[13] Regrettably, these "raw materials" are rarely utilized in government programs, causing the frequent waste of "reinventing the wheel." The reason is the contractual isolation of different PD programs, motivated by a bureaucratic fear of co-mingling of funds.

Gantt chart. Participation of a high-level manager from that program in the VS mapping of the current program is highly desired. Each Task sheet should have fields for:

1. Task number and the week of execution (left blank until Future State mapping)
2. The person responsible (name, title, telephone, cell, email, location; again left blank)
3. Major inputs, each indicating the source Task
4. Major outputs, each indicating the destination Task and approval or control nodes
5. Effort, resources, and scope
6. Issues, notes, comments

The tasks should be temporarily placed roughly in the weeks in which they were executed on the last program. Where available, the notes should indicate the waste for subsequent removal, e.g., the time of waiting for or chasing the data, approvals, handoffs, rework, "reinventing the wheel," etc. (see also Box 2).

This is a messy, iterative process but it offers huge payback potential in the Future Step mapping. As mentioned above, the manual by McManus [2004] will be helpful in this step.

Next, or concurrently, the Tasks from the legacy program should be amended and modified to reflect the current contract. From this point on, this effort should be handled by a complete Program Core Team comprising of experienced functional managers representing all major system components, candidates for various Team leaders, and representatives of major suppliers. If the team writing the proposal were different from the Core Team, the former should be represented during the mapping effort.

Brainstorming, negotiations, and iterations are the most productive means at this stage. The Chief Engineer experienced in PD VSM and possessing good motivational skills should lead the effort. The present focus should be on listing *all* tasks and their waste, rather than on any task or flow optimization, which will come later, during the Future State mapping.

Mapping the Future State. This step has a potential for huge direct payback often measured in millions of dollars saved from the program per hours of effort; therefore, it should be performed as comprehensively as possible.

The Core Team may conclude that the program involves one or more big uncertainties, which would pose risk to the program schedule if left within the main workflow. Each such uncertainty should be isolated from the main flow, placed on a separate track, assigned to a separate team, and staffed to resolve the uncertainty in time for deployment in the main flow. The separation of research, development and program deployment are discussed in Box 9, point A, in more detail.

The PD process is normally too complex and driven by too many stakeholders and driving functions to make any formal unique optimization possible. Therefore, it makes sense to focus only on the identification of value and reduction of waste. The Current State map displayed on the walls becomes the basis for the iterative waste removal, and for improving task concurrency, synchronicity, precedence, and the general flow. Experience indicates that some NVA is self-evident and easy to remove, some NVA and RNVA will require brainstorming and negotiations within the Core Team, and some may never be discovered. The problems and solutions experienced during former programs are a good starting point.

In general, any and all established tools currently used at the company for process mapping, task scheduling and precedence, concurrency, and synchronicity studies should continue to be used at this LPDF stage. The manual of McManus [2004] is recommended as a practical tool for this phase of the mapping, too. Suggestions for concise characterization and connections of tasks, including inputs and outputs, are available in Negele et al. [1999] and Rouse and Boff [2003]. The Design Structure Matrix (DSM) may be used for compact analysis of single-level task precedence and team grouping, supported by Internet software tools [Browning, 1999a]. DSM tools may also be used for multi-level programs but under complex circumstances can be vulnerable to instabilities [Sharman and Yassine, 2004]. In addition to being a science, design is still an art inherently mixing a large number of tangible and intangible, and qualitative and quantitative constraints and human factors, therefore mathematical tools such as Petri-nets, Queuing Theory [Shin and Levis, 2003], or rigorous software architecting tools such as IDEF [1993] appear to have at best a limited utility in LPDF.

Parsing the Future State Map into Takt Periods. The next effort of VSM is to parse the Future State Map into Takt Periods. This step and the Future State Mapping will normally require iterations together. Again, the entire Core Team should participate to enable iterative brainstorming and negotiations. The dynamic allocation of matrix resources during different Takt Periods should be addressed at this stage. The parsing may open additional opportunities to remove waste.

Goldratt [1997] proposed parsing the work into small logical packets. The present approach goes a step farther, parsing the work into Takt Periods of short and equal duration, with all Tasks of equal duration but not necessarily equal loading or effort. The application of Takt Periods is an absolute requirement for the steady flow.

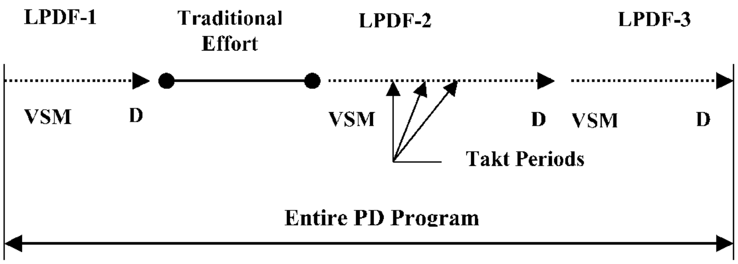

Figure 3. Dividing a long PD program into LPDF and traditional sequences.

Clearly, in any complex flow involving hundreds or more people, unexpected events (and uncertainties and design changes) will be likely, requiring adjustments to the schedule, as they do on automotive assembly lines. The general attitude of the Core Team should be to map the best VS possible, but also to prepare for flexible handling and mitigation of the changes. PD experience indicates that an imperfect plan is better than none. Even an approximate scheduling of resources should be helpful to the functional managers in their planning.

The role of the Chief Engineer is to guide the Core Team towards consensus on the VSM. The mapping should continue until that goal is met, that is, until every Core Team member accepts the final parsed VSM, and declares readiness to provide the required resources and execute the Tasks.

The detailed VS mapped into short Takt Periods at the program beginning forms a detailed flow plan and schedule. Theoretically, the subsequent monitoring of the program progress could be as simple as checking off the Task boxes in the VSM. This should reduce the need for the "heavy-handed and bureaucratic" capability maturity matrices recently mandated within the defense industry [Phillips, 2002].

Long and Multilevel Programs. The LPDF process should be applied to the entire PD effort provided that the VSM can be created for the entire program with sufficient fidelity and parsing. If the entire program is too long, too complex, too discontinuous, or subject to excessive uncertainties for a single application of LPDF, the PD program should be divided into several pieces or milestones with the LPDF process applied separately to one or more of the pieces, not necessarily contiguous. The subdivision does not need to be based on equal-duration pieces, and instead should be based on logical milestones. Each piece should then be treated as a separate LPDF, with its own value proposition and specification of the final deliverables, own VSM, flow, pull, and perfection, as well as cost and schedule. The different LPDF programs should be joined as seamlessly as possible, avoiding the risk of sub-optimization. Figure 3 illustrates such a multi-LPDF sequence. A downstream LPDF should pull the deliverables (labeled "D" in Fig. 3) from the upstream LPDF.

More complex systems may require several levels of effort. Table III lists an example of different levels in a multilevel spacecraft-based PD program.

The LPDF process can be used to organize a multilevel program, provided that the following conditions are satisfied:

- Each level is organized as a separate LPDF.
- Each LPDF must have its own Chief Engineer.
- All LPDF programs executed concurrently must follow the same Takt Periods, but the Integrative Events should be shifted by 1 day to enable participation of representatives of the other levels.
- Meeting every second or third Integrative Event may be sufficient for some levels (typically the top level).
- Typically, coordination will be needed between three levels at a time: "our level," the next higher level, and selected lower-level teams.

Clearly, a multilevel LPDF will be more difficult to manage than a single-level one. Under the name of Design for Integration, Browning [1999b] includes a discussion of system integration issues in multilevel teams. The discussion covers decomposition, integration, organizational design, flexibility, team size, interface characteristics, training, co-location, town

Table III. Example of Levels in a Multi-Level Program

LEVEL	HARDWARE EXAMPLE
Super system	Spacecraft(s) + Launch + Ground support
System	Spacecraft
Subsystem	Payload, frame, bus, battery, solar panels, propulsion, star tracker, antennas,..
Component	Battery cell, a solar panel, thruster,..
Sub-component	Parts of components.

SUCCESS FACTORS

1. Availability of a large comfortable "War Room" suitable for VSM, for the Program duration
2. Consensus of the Core Team on the Program schedule
3. Consensus of the Core Team on the Final Value Stream Map parsed into short Takt Periods
4. Consensus of the Core Team on the LPDF team organization

SUCCESS METRIC

Amount of waste removed when mapping from Current State to Future State ($, or time units).

Box 4. Success Factors and Metrics for Lean Principle 2

meeting, mediation by manager and by participants, interface management groups, interface contracts and scorecards, and checklists, as well as the need for an early foresight of organization design.

Designing the Team. The last obligation of the Core Team is to design the LPDF team architecture, including the planning of the dynamic employee allocation during the flow. LPDF places few constraints on the team architecture. The employees can be organized into any configuration that makes sense to the Core Team, including long-term and short-term teams, system teams, and subteams, groups or individuals dynamically allocated from their home departments in a matrix organization, or separates individuals (e.g., hired experts or supplier representatives). In LPDF programs using matrix organizations, it is important to have the department heads evaluated, among others, on the basis of the degree of support they provide to the LPDF Chief Engineer.

There is no single winning configuration, and various successful organizations follow a broad range of practices. Allen [2002] addressed the optimum balance between functions and teams in PD programs based on the rate of change of technology, the degree of subsystem interdependencies, project duration, and market volatility. Browning [1999b] presented practical considerations for selecting team sizes.

Box 4 lists four success factors and one metric proposed for Lean Principle 2.

LEAN PRINCIPLE 3: MAKE THE WORK FLOW

The ideal LPDF flow is a steady progress of the value stream through all Takt Periods, with maximum coordination and minimum waste, each Period terminating with an Integrative Event, Figure 1, with the flow beginning as soon as the VSM is completed, and ending when the final deliverables are released to the satisfaction of the stakeholders, within schedule and budget.

Takt Periods. The equal Takt Periods serve to provide absolute, nonnegotiable common deadlines for *all* team members to robustly complete all the Tasks assigned for the given Period. The equal common deadlines are needed for the following reasons:

(i) To impose the discipline motivating everybody to work to the common rhythm, as on a moving line[14]
(ii) To provide critically needed frequent and periodic common opportunities for the entire team to coordinate work, identify and resolve issues, and flexibly adjust the plan for subsequent work
(iii) To assure predictable flow of the Value Stream and the program progress.

The distribution of work among the individuals, teams and departments depends on the work demands within the given Takt Period and should be dynamically handled as needed. The workload of different teams and departments will vary from Period to Period, symbolically illustrated in Fig. 1 by Task boxes A, B, C, etc. being of different sizes in different Periods. Also, not all Tasks need be active during all Periods, as symbolically indicated in Fig. 1 by some boxes being absent from some Periods. During each Takt Period, work is carried out according to the original VSM, or the VSM adjusted by the Chief Engineer during the flow in real time.

All employees should be trained for the special needs of LPDF. The extent of the training is discussed under Lean Principle 5. Preferably, all LPDF team members should receive a booklet describing the critical information nodes, including who (names, responsibilities, email, location, phone, and FAX) is doing what work, and a list of work protocols.

Efficient concurrent work on multiple Tasks during any Task Period will typically require unstructured, and

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[14] Since biological rhythms (heart beats, days/nights, and seasons) are natural to humans, a work rhythm should be useful, too.

occasionally intensive, communications between team members. Every person who has a question regarding the homework or data should immediately contact the information source or destination, as applicable, without waiting for the Integrative Event. Everybody should follow the pull principle, learning who is the internal customer (recipient) of the work results, and efficiently negotiating the information transaction. The Core Team led by the Chief Engineer should monitor all work.

Each team member should report any serious concern or interdisciplinary issue immediately to the office of the Chief Engineer (described under Lean Principle 5), without waiting for the Integrative Event. The Chief Engineer and his staff should be available for guidance, mentoring, even ad hoc training, if needed, as well as general management of the flow.

Given the intrinsically tight schedule of LPDF, robust and timely completion of the Tasks is critically important. The Chief Engineer should insist that the lack of success will be justified only as a rare exception for only incontrovertible reasons. Tasks should be staffed, and people trained, accordingly. The role of LPDF management is to provide the resources, coordination and training required to make it possible.

In order to best utilize the precious time of Integrative Events, managers and key engineers should prepare brief (1–2 pages) notes on issues that require cross-functional coordination, including the diagnosis of the problem or tradeoff, key information, and recommendations, for the Chief and the team to address during the next Event. Toyota provides an efficient model for the preparations [Sobek, Liker, and Ward, 1998].

Integrative Events. An Integrative Event is a meeting where the work results are comprehensively coordinated, verified for consistency with the value proposition, and prepared for the next Takt Period(s). As Browning [1999b, p. 218] points out:

> … [C]omplex system development implies complex organizations...[People] working together to develop complex systems face a daunting task. They depend on each other for information (sometimes without realizing it). They must interact. A team producing at the fastest rate humanly possible spends half its time coordinating and interfacing. …

A call for more comprehensive coordination of work, both structured and unstructured, is a consistent theme in the author's contacts with the PD community.

In contrast to the unstructured communications taking place during the Takt Periods, the Integrative Events are intended for more structured coordination. The Chief Engineer, or an Assistant Chief delegated by the Chief, should define the Integrative Event agenda, structure, and lead the meeting. Box 5 lists selected topics recommended for the Integrative Events.

SAMPLE TOPICS FOR INTEGRATIVE EVENTS

a. Efficient review of progress. Chief or Assistant Chief asking pointed, knowledgeable questions of the participants, including the numerous questions "why?" asked in a nonconfrontational style
b. Comprehensive coordination of work
c. Resolution of tradeoffs, concerns, issues, and building consensus—if practical, in breakaway sessions, involving only the needed individuals
d. Identification, management, and retirement of program risks
e. Identification and flexible mitigation of uncertainties (when appropriate, treating uncertainties as opportunities for creative and entrepreneurial solutions)
f. Exploration of design spaces versus point designs
g. Optimization and coordination of the inevitable iterations for minimum effort and cost
h. Decisions whether to insert knowledge from legacy programs
i. Involvement of suppliers and other stakeholders
j. Balancing between new and mature technology, and between creativity and standards
k. Re-use of modular subsystems and checklists from former programs
l. Balancing tradeoffs between design margins and the analysis fidelity
m. Discussion and decisions on which analysis, tests, and documents are needed, resisting those deemed wasteful
n. Adjustments of VSM, assignment of adjusted work to responsible parties, and allocation of necessary resources
o. Addressing any and all big relevant questions
p. See also Browning [1999b], for other coordination topics under the broad heading of "Integrative Mechanisms."

Box 5. Sample Scope of Integrative Events

SUCCESS FACTORS	SUCCESS METRICS
1. Discipline of completing robust work within each Takt Period 2. Availability of dynamically allocated resources, as agreed during the VSM 3. Efficient mitigation of uncertainties (resulting in no schedule delays)	1. VS schedule completed as expected 2. Good morale of the LPDF team (can be measured by anonymous periodic questionnaire)

Box 6. Success Factors and Metrics for Lean Principle 3

It is obvious that the scope of Integrative Events should extend well beyond the frequent practice of status reviews. The meeting just described must be conducted systematically, following a structured agenda, and last as long as needed to address all the important questions. One day of each Takt Period should be more than enough for the typical weekly Integrative Event. Holding it on Fridays offers the weekend buffer for urgent catch-up work. Face-to-face interactions between participants are strongly preferred during the actual coordination, provided that the individuals are prepared and trained. Strict policies should be in place for pull-based dissemination of documents intended for the Integrative Events; otherwise the team may become overwhelmed with pushed data.

The Integrative Events should be recorded to enable easy recall, and to augment corporate memory for future PD programs.[15]

The tight schedule and disciplined flow of work require a number of enablers, which are discussed under Lean Principle 5. Box 6 lists the success factors and metrics suggested for Lean Principle 3.

LEAN PRINCIPLE 4: PULL

> An unreleased [...] study has found that an alarming percentage of PD process outputs are not needed by downstream processes, for program knowledge capture, for meeting regulations, contractual requirements, or quality standards, or for any other purpose. They are waste. [McManus, 2004, p. 108]

This paragraph describes the PD equivalent of the "push": the work scope and schedule, which are decided by the creator without regard for the recipient. The Lean Pull Principle is the critical guard against the waste of unneeded work and associated rework. It promotes "doing the right work right." The Tasks should be specified only if needed by a downstream process, and that process should define the work scope, consistent with the value definition. This imposes a discipline on each LPDF team member to:

a. Learn who is the recipient of each Task output (i.e., who is the "internal customer")
b. Become familiar with the needs of the recipient
c. Negotiate the transaction with the recipient, if necessary.

Box 7 lists the success factors proposed for Lean Principle 4.

In contrast to Lean manufacturing, where each receiving work station uses Kanban to signal to the supplying station the readiness (i.e., "the need") for the next part or work-in-progress, the meaning of Kanban in design is different because there are no "next parts"; PD tasks are executed one time, with deliverables (outputs) passed to the next tasks as soon as finished to eliminate waiting. The status of the deliverables should be monitored on the VSM and delays addressed during the Integrative Events. Good communication is critical in order to assure efficient flow of information without backflow, including the aspects a–c. More traditional Kanban signals may be useful in LPDF when the value flow departs from the ideal, e.g., when performing repeated multi-functional iterations, or when handling delays or schedule changes ordered by the Chief Engineer. These Kanban signals can take the form of emails, phone calls, or more formal documents or meetings.

LEAN PRINCIPLE 5: PURSUIT OF PERFECTION

A costly PD program must succeed on the first attempt. Therefore, the fifth Lean Principle "Pursuit of Perfection" must be interpreted as pursuit of both perfect planning of LPDF, i.e., VSM (described under Lean

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[15] Video may be used as an efficient record-keeping device for memory jogging, provided strict rules are in place prohibiting any use of the video for staff evaluations, contractual compliance, or other such abuses.

SUCCESS FACTORS

1. Every Task "owner" knows who is the internal customer.
2. Every owner understands the deliverables scope, format, and functionality needed by the customer.
3. In case of disagreement between the Task owner and internal customer, negotiations should end with a mutual compromise without compromising the LPDF value proposition.

Box 7. Success Factors for Lean Principle 4

Principle 2), and perfect first-time execution of the flow. A detailed comprehensive VSM is a necessary but not sufficient condition for the LPDF stability. Destabilizing events in the form of uncertainties and program changes are notorious in PD programs, as discussed by de Neufville [2004], in a seminal treatise on the frontiers of present and future engineering thinking about uncertainty, and by Hastings and MacManus [2004], who present a broad classification of PD uncertainties and a review of techniques for mitigating and even taking advantage of them. The fast flow of value stream makes LPDF particularly sensitive to the instabilities. Over the last century, significant knowledge, experience, and effort have been devoted to the design of flow in automotive lines, and yet, today, even the best assembly lines still suffer from frequent stoppages due to unexpected problems.[16] Therefore, it would be naïve to expect no problems in a LPDF flow. The problems require special mitigating strategy and tactics, which are described under three following enablers: Program Leadership and Management, Training, and Management of Uncertainties and Unexpected Events.

Program Leadership and Management. Good leadership cannot be delegated. A highly skilled leader named the Chief Engineer should lead the entire LPDF program. The present model is a synthesis of Toyota's model of the Chief Engineer [Sobek, Ward, and Liker, 1999], and Honda's model of the "Heavyweight Project Manager" [Clark and Fujimoto, 1990]. The person's job description should be to "produce the required product or assure the mission to the satisfaction of the customer, within budget and schedule," and the person should be evaluated only by how well this goal is met. The Chief must be the sole "owner" of the program, totally responsible for the program (concepts, tradeoffs, key design decisions, coordination, targets, schedule, and budget), but should have formal authority over only a small direct staff. Box 8 contains a summary of the desirable attributes of the Chief Engineer and Assistant Chiefs.

The company involved in LPDF programs should groom several Chief Engineers for each major product type, supporting their professional growth and education, exposing them to challenging experiences, and rotating them through major departments. The candidates should be carefully selected from among the best and brightest, both technically and for their interpersonal skills.

Early aerospace and defense programs used the equivalent of a Chief Engineer [Rich and Janos, 1994]. The unfortunate recent industrial practice has abandoned the Chief's position, dissolving the integrated responsibility among poorly defined teams, the Program Office, a typically weak and administratively focused Program Manager, and engineering departments.[17]

Recent defense contracts have been burdened with vast administrative responsibilities, tracking costs, schedule, manpower, subcontracts, program maturity, complex reports, approvals, and releases, all handled within a significant corporate bureaucracy. To the degree possible, LPDF proposals and contracts should be written to minimize such RNVA activities. Traditionally, the office of the Program Manager has been responsible for handling the PD administration, focusing on cost and schedule, often at the expense of mission assurance. In LPDF, the roles should be reversed: mission assurance is regarded as the most critical part of the value proposition, with administration supporting the value creation rather than competing for resources, but at the same time focusing on the elimination of waste. The Chief Engineer should be totally responsible for delivering the product value, directly focusing on product integrity and good engineering, while the Pro-

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[16] The author observed a Toyota line in the NUMMI plant in Fremont, California, recognized as one of the best in the world, stopping several times per hour while assembling a mature car model.

[17] Contrasting the frequent cost and schedule overruns of the recent U.S. aerospace programs with the consistent success of Toyota, Honda, and the earlier U.S. aerospace programs managed by strong leaders may be indicative of the need to re-adopt the position of the Chief. This is surely not the only one, but probably an important factor.

CHIEF ENGINEER

- "The most coveted job in the Company."
- "The buck stops here." LPDF success relies on the extraordinary leadership, competence, and experience of the Chief Engineer and the dedication of the Core Team, and their freedom to pursue the program as they think fit, constrained only by the personal, program, and product integrity. The Chief must be made the sole owner and leader of the program, eager to guide difficult tradeoffs (such as which tests or requirements to skip or how big should be the margins) on a case-by-case basis, brainstorming with experts and studying issues but ultimately assuming full responsibility for final decisions. The overall focus should be on value (mission integrity) and elimination of waste. The corporation and the contract must support this. Conservative bureaucratic procedures, methodologies which dissolve responsibility should be avoided.
- Freedom to select Assistant Chiefs. The Chief must have the freedom to select a few Assistant Chief Engineers complementing the Chief's expertise, whose loyalty are to the Chief, the end customer (i.e., the program), and the company, and not to any particular functional department from which they came. The Chief alone should evaluate the Assistant Chiefs.
- Focus. Never ending focus on customer satisfaction, program value and integrity, product concept, and reduction of waste.
- Interpersonal skills. Ideally, a good leader, with a high degree of credibility, who is free of a domineering personality. Leading and motivating for excellent performance using a nonconfrontational style. More like a movie director or symphony conductor than a traditional program manager. In frequent personal contact with engineers, but without micromanaging unless selectively necessary. High level of interpersonal skills to guide the team towards consensus during the value proposition and VSM work, when resolving issues during Integrative Events, and when negotiating with the company for resources. Ability to delegate and draw on team members' competence, experience, and creativity.
- Education. Preferably a master's degree in Systems Engineering, or a master's degree or equivalent in the product domain, with at least several courses in Systems Engineering.
- Experience. Solid understanding of all critical first-level subsystems, their interfaces, and tradeoffs. Experience in the capacity of an Assistant Chief Engineer on at least a few programs. Knowledge of frustrations, problems, and solutions experienced in former programs. Alternatively, a high-level manager from a legacy program should serve as Assistant Chief. Understanding of company culture and structure. Preferably most professional years spent rising through the ranks and rotating through major departments as an active engineer. Record of lifelong learning, attending professional conferences, and following literature.
- Compensation. Clearly, the Chief's compensation should be proportional to the exceptional role the person plays and the vast responsibility.

Box 8. Summary of Desirable Attributes of Chief Engineer and Assistant Chief Engineers

gram Manager reporting to the Chief should handle all the program administration separate from the main work flow, or as a parallel flow. The Chief should be ultimately responsible for balancing the engineering case with the business case, quality with schedule, and innovation with legacy.

Team Training. LPDF is sufficiently different from traditional PD programs that all participants should receive a proper training in that process (about 1 day of training roughly structured along the organization of this paper). They must understand the role of VSM and the critical need for the discipline of Takt Periods. They should be trained to identify and rebel against PD waste, and promote the program value. They must be aware of the non-negotiable aspects of the flow (the deadlines of Takt Periods and product quality/program integrity), and the negotiable aspects (resource allocation, flexible coordination). The role of the LPDF Chief Engineer, Assistant Chiefs, and Program Manager should be well understood, including the welcomed interactions with these leaders. Everybody should be empowered "to stop the line" by bringing concerns and issues to the attention of the Core Team. The entire team should receive proper training in the vastly increased role of commu-

MITIGATING UNCERTAINTIES

A. Strategic Separation of Research, Development and Deployment. Since research progress and cost are inherently difficult to schedule, research should not be a part of the PD flow. In contrast, robust mature technology (RMT) can be predictably scheduled and budgeted, so it is favorable to rigid-schedule programs. In general, the companies must perform all three: research (needed in order to stay competitive), development, and design, but should clearly separate them, as follows. Research should be an ongoing long-term strategic effort pushing the knowledge envelope and acquisition of the latest technology, independent of short-term programs. Well-organized research output should be in the form of technologies that are mature enough to be made robust but are not yet so. Functional engineering departments should then take the research output and translate it into RMT, modularized and packaged to the maximum degree for usability, manufacturability and low cost. Finally, LPDF teams should deploy the RMT into the program, as if taking off-the-shelf items. In doing this, functional departments should support the teams, and research staff should support the departments. The key enabler is to organize an efficient flow of knowledge from research, to RMT and on to LPDF team. Rouse and Boff [2003] offer a discussion supporting this point.

B. Separation of R&D from LPDF. During the VSM, the big "known unknowns" which could destabilize the program and schedule should be identified, declared to be Research or Development Tasks, placed on a track separate from the main work flow, and staffed and supplied with sufficient other resources to yield the results when needed by the main work flow.

C. Balance Between Robustness and Flexibility. As de Neufville [2004, p. 10] pointed out, robustness is "the ability to take the blow," while flexibility means "stepping away from the blow," an imminently better approach. Both robustness and flexibility of design and processes should be a part of LPDF strategy. The enablers include the initial training of the LPDF team, and ongoing leadership by the Chief Engineer.

D. Set-Based Designs. As pointed out by Sobek, Ward, and Liker [1999], Toyota PD practice indicates the strong strategic superiority of set-based designs over point designs. The former vastly reduces the need for iterations. The Chief Engineer should guide the balance between set-based and point designs.

E. Design Context. Morgan [2004] points out that considering design options in the next larger context is conducive to PD stability. If not practiced, the ignored context constraints may hamper the later program progress. Team training and LPDF leadership are the enablers.

F. "Delicious Chaos." As de Neufville [2004] suggested, unexpected uncertainties should be regarded as opportunities for new creative entrepreneurial solutions rather than as program stoppers. The Chief Engineer should guide the tradeoff between creativity, on the one hand, and standards and legacy knowledge, on the other.

G. Margins.There is a tradeoff between initial design margins and the need for expensive high-fidelity analysis and testing. The high costs of engineering labor usually favors starting with large margins. The Chief Engineer should guide this tradeoff.

H. Legacy Knowledge. Starting the VSM work with legacy knowledge prevents the waste of "reinventing the wheel" and is conducive to the elimination of past uncertainties, failures, and mistakes. The Chief Engineer should lead the tradeoff between the legacy solutions and new development.

I. Modularity. Predesigned (if not prebuilt) modules for re-usable components, and re-usable platforms reduce uncertainties, and design and testing work. The Chief Engineer should interact with the company regarding the choice of components and subsystems suitable for modularization, consistent with the long-term company strategy.

J. Iterations. Engineering design inevitably involves iterations to provide solutions to the technical "chicken and egg" problems. Poorly handled iterations tend to introduce delays and destroy schedule and budget. The answer is in faster and more efficient handling of those iterations, which are inevitable after other mitigation strategies have been exhausted, such as set designs, legacy knowledge, large margins, and creativity. The remaining iterations should be well managed for minimum effort [Warmkessel, 2002]. Information should be flowed efficiently within and between the iterations.

Iteration loops should be critically scanned for potential waste, such as including too many tasks in the loops, or too much analysis repeated within a task. The iterations that are known or likely to occur should be planned as regular tasks in the VSM. Unexpected iterations should be compensated with dynamic allocation of resources in order to keep the schedule. Good initial training of the LPDF team is the main enabler of this feature.

K. Need to Estimate. Complex simulations should be avoided in early design stages because they often require a massive number of accurate inputs, which are still unknown, thus causing waiting and schedule delays. Instead, experience and knowledge of senior engineers and experts should be employed to estimate parameters during early analyses. Results from former programs can be extrapolated where applicable. Again, the Chief Engineer should guide the tactical choices between the fidelity and model sophistication on one hand, and the LPDF schedule and budget on the other.

L. Care with "Unknowns." Not every "unknown" that appears to a junior engineer should be elevated to a formal status of uncertainty or risk, which require special statistical, systems, and administrative burden. Often, a more experienced engineer or scientist may provide the answer immediately. Some guidance to the team should be given during the initial LPDF training.

M. Reporting Anomalies. Every team member should immediately report any anomaly or discrepancy from the original assignment or schedule to both the internal customer and the Core Team. The Chief should provide guidance for the reporting protocol.

N. Unknown Unknowns. The dynamic allocation of people is a good mitigation strategy for handling the hopefully rare "unknown unknowns" type of uncertainties. If a major unexpected event occurs, the Chief Engineer will need to decide whether to increase the staffing and meet the schedule, or keep the current staffing and accept a schedule delay, use overtime, or choose an intermediate alternative.

O. Minimizing the Churn. The frequent Integrative Events decrease the information churn effect and are conducive to early identification of uncertainties and opportunities for immediate corrective action, including flexible adjustments of Tasks and their work synchronicity, precedence and concurrency, and the handling of engineering changes.

Box 9. Summary of Practices and Enablers Recommended for Mitigating Uncertainties

nications and coordination needed for the success. Each participant should learn the program communication nodes, in particular who is one's internal customers and what are the customer needs. The protocols for preparing for and participating in the Integrative Events should be explained. The training should also include elements specific to a given program, and to the individual leadership style of the Chief Engineer. The training should be organized by the Chief and delivered in a most positive manner, encouraging the best human outcomes: engagement, excellent team dynamics, high expectations, and the feeling of participating in a challenging and fun project.

Mitigation of Uncertainties and Unexpected Events. The PD uncertainties can vary from routine, manageable, to overwhelming, destructive to the program. Efficient strategic and tactical mitigation of uncertainties is critical to the LPDF success. Team training and flexible leadership by the Chief Engineer are the prerequisites.

Hastings and MacManus [2004] organized PD uncertainties, risks and opportunities, mitigations and exploitations, and outcomes into an elegant framework with ample examples. Uncertainties are classified into: lack of knowledge (from trivial to serious, requiring an R&D), lack of definition/specification, lack of statistical characterization, known unknowns, and unknown unknowns. Among the mitigations, they list: margins; redundancy; design choices, design space exploration, and portfolios & real options; verification and test, generality, upgradeability, and modularity. De Meyer, Loch, and Pich [2002] presented practical strategies for mitigating a similar class of uncertainties, namely: variation, foreseen uncertainty, unforeseen uncertainty, and chaos. Box 9 summarizes the practices and enablers that are recommended for mitigating the uncertainties, based on the last two and other indicated sources, and the author's personal experience.

Box 10 lists the tactical and strategic success factors proposed for Lean Principle 5.

TACTICAL SUCCESS FACTORS

1. Implementation of effective LPDF leadership, led by a Chief Engineer who is free to select a few Assistant Chiefs and a small staff, as well as a competent Program Manager to assist with the LPDF administration
2. Effective Training of the entire LPDF team prior to the Value Stream Mapping
3. LPDF progress according to the VSM schedule
4. Effective and flexible handling of VSM adjustments, if any, and engineering changes, without crises or major delays

STRATEGIC SUCCESS FACTORS

1. High morale, team dynamics, and energy of the LPDF Team (easy to evaluate by questionnaires)
2. Program completed within budget and schedule to the satisfaction of the customer

Box 10. Strategic and Tactical Success Factors for Lean Principle 5

4. PILOT IMPLEMENTATION

At the time of this writing (Spring 2004), the proposed LPDF process is being tested on a pilot project at a major U.S. satellite maker. The program is estimated to take 2 years. The author intends to publish the results, when available, as a companion paper to the present one.

5. SUMMARY AND CONCLUSIONS

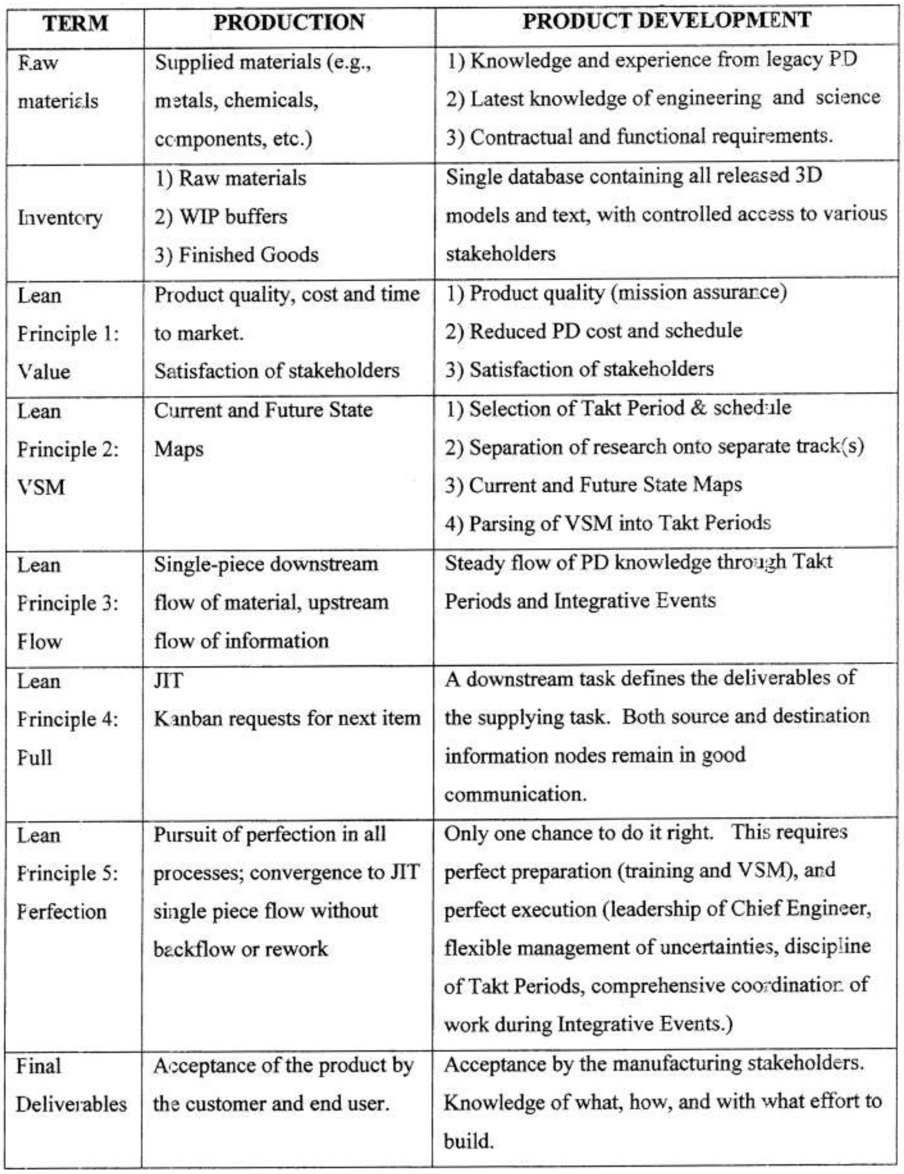
The paper presents a general holistic framework (also referred to as a process)—named Lean Product Development Flow (LPDF)—for organizing the effort of technological Product Development. LPDF is based on the same powerful five Lean Principles that yielded extraordinary benefits in production applications by organizing the work as an uninterrupted flow proceeding through all processes at a steady pace, without rework or backflow. The ultimate intent of the proposed LPDF is to reproduce this success in Product Development (PD) work. More specifically, the intent is to radically shorten the overall PD schedule and cost by an aggressive reduction of the all-pervading waste, without sacrificing the value, as defined by all the traditional quality goals of Systems Engineering. The process is being proposed as a contribution to the emerging field of Lean Systems Engineering. The LPDF value is defined as (1) mission assurance/product quality (the traditional goal of Systems Engineering) and (2) reduced program cost and schedule by a radical reduction of waste, and the associated reduction of daily frustrations of the PD team. The process is organized as a value-pulling workflow pulsed by Takt Periods.

LPDF is recommended for smaller developmental programs based on a high degree of legacy knowledge, with predominantly mature technologies and low risk of major uncertainties. The paper is focused on the aerospace and defense programs, which are presently burdened with as much as 60–90% of waste, but the process is also applicable to commercial programs. LPDF may involve limited-scope research provided that it can be identified early in the program and carried out separate from the main work flow. LPDF favors shorter programs for which the risk that major product or process technology changes could disrupt the flow is small. The program scope should be limited to the field of Systems Engineering, including all its relevant subdisciplines, as well as engineering design and sciences, and supporting business practices. Such program may still face taxing uncertainties and technical challenges of meeting margins, as well as production, assembly, and integration issues; however, the program feasibility should not be in question, and the small delays due to the issues can be compensated by the corresponding small adjustments to the schedule and dynamic allocation of resources. LPDF can be applied to the entire PD, to one or more of its milestones, and, by extension, to multilevel programs.

The paper demonstrated direct analogies between Production and LPDF domains, as summarized in Table IV.

The paper describes both preparations and execution of the LPDF process. Both must be perfect because LPDF has only one chance to be successful. The prerequisite preparations require team training, selections of the Takt Period and program schedule; detailed Current and Future-State Value Stream Mapping; separation of big uncertainties from the main workflow into parallel research and development effort; parsing of the VSM into Takt Periods; and architecting the LPDF team. The execution requires disciplined flow of work in concurrent Tasks completed within Takt Periods, structured management of the Integrative Events, stra-

Table IV. Analogies between Production and Product Development



TERM	PRODUCTION	PRODUCT DEVELOPMENT
Raw materials	Supplied materials (e.g., metals, chemicals, components, etc.)	1) Knowledge and experience from legacy PD 2) Latest knowledge of engineering and science 3) Contractual and functional requirements.
Inventory	1) Raw materials 2) WIP buffers 3) Finished Goods	Single database containing all released 3D models and text, with controlled access to various stakeholders
Lean Principle 1: Value	Product quality, cost and time to market. Satisfaction of stakeholders	1) Product quality (mission assurance) 2) Reduced PD cost and schedule 3) Satisfaction of stakeholders
Lean Principle 2: VSM	Current and Future State Maps	1) Selection of Takt Period & schedule 2) Separation of research onto separate track(s) 3) Current and Future State Maps 4) Parsing of VSM into Takt Periods
Lean Principle 3: Flow	Single-piece downstream flow of material, upstream flow of information	Steady flow of PD knowledge through Takt Periods and Integrative Events
Lean Principle 4: Pull	JIT Kanban requests for next item	A downstream task defines the deliverables of the supplying task. Both source and destination information nodes remain in good communication.
Lean Principle 5: Perfection	Pursuit of perfection in all processes; convergence to JIT single piece flow without backflow or rework	Only one chance to do it right. This requires perfect preparation (training and VSM), and perfect execution (leadership of Chief Engineer, flexible management of uncertainties, discipline of Takt Periods, comprehensive coordination of work during Integrative Events.)
Final Deliverables	Acceptance of the product by the customer and end user.	Acceptance by the manufacturing stakeholders. Knowledge of what, how, and with what effort to build.

tegic and tactical mitigations of uncertainties, and excellent communication and coordination both between and during the Integrative Events. The challenging flow requires excellent leadership of a Chief Engineer (modeled after Toyota and Honda), who is the dedicated program "owner," a strong leader skilled in consensus-building, focused on the program and product integrity, an expert systems designer, and an exceptional program manager. The Chief Engineer should be in charge of the entire program, with Assistant Chiefs assisting in selected technical areas and a Project Manager assisting with the program administration.[18]

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[18] The discipline of Takt Periods and VSM inherent in the LPDF might suggest that the program might automatically become a "turn-the-crank" effort void of challenges, and turn the best and brightest engineering stars away from the role of the Chief Engineer. This impression would be totally wrong. In general, Lean implementations are widely known for demanding strong creativity, problem-solving spirit, involvement, experience, and coordination skills, and tend to attract the best and brightest. The Toyota Chief Engineers never complain about the lack of challenges, even though Toyota programs are possibly the most heavily scripted and mature of any Lean systems. The intellectual challenges in LPDF are bigger than in manufacturing, because program development (a) has a much bigger impact on the overall program cost than manufacturing, (b) requires better coordination between more knowledge nodes, (c) involves the state of the art knowledge, and (d) is a new approach with no experience do draw from. The challenges start with expert-level

Several of the LPDF elements recommended here have been described in the quoted literature. Each element alone should be conducive to better value delivery and waste reduction even without the strict implementation of LPDF. In this category are good strategic and tactical management of uncertainties, frequent and comprehensive reviews, good training, leadership, detailed planning and VS mapping, the pull of requirements, and others. LPDF integrates these previously known features, and a number of new ideas, into a synergistic Lean flow with a powerful potential for creating value (mission assurance), and radical reduction of the huge PD waste, making similarly radical cuts in cost and schedule possible.

Arguably, two elements of LPDF appear controversial. The first is the requirement for detailed mapping and parsing of the Value Stream into short and equal Takt Periods. The concern is about its practicality, not merit. Common wisdom calls for a "good planning" at the beginning of PD programs. Experience-based, consensus-created, competition-motivated, optimized VSM parsed into short Takt Periods is unquestionably the ultimate good plan. Its practicality depends on the company culture. The fear of competition, good leadership of LPDF, good training of the team, and support of top management are the best enablers of the culture change. Even if the VS were not mapped to the fidelity recommended herein, it would be better than no VSM, or the traditional lackluster Gantt chart. An imperfect VSM can be adjusted in real time during the frequent Integrative Events, which offer inherent flexibility for mitigation of unexpected events and dynamic allocation of resources.

The second "controversial" element of LPDF is the disciplined work execution within short Takt Periods. Compelling arguments have been presented in favor of this approach. If not followed as recommended here, the penalty to the program would be less-than-full benefit but hardly an increased risk of mission integrity. The resultant penalty in cost and schedule should not be worse than that of the recent traditional programs. In other words, LPDF is regarded as a proposition with potential for radical benefits, and with no cost or schedule risk beyond those of traditional programs.

An industrial pilot program is currently being undertaken to test LPDF. Results should be available within 2 years and will be published as a companion paper. Circumstantial evidence collected from a number of Lean Aerospace Initiative programs containing some PD work suggests potential for radical (25–80%) schedule and cost reductions from the use of various Lean approaches.

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remapping of a legacy VSM for the new mission success using the Takt Period parsing and aggressive intensive elimination of waste. Then, during the program Flow, the breadth and depth of effort listed in Boxes 5 and 9 present strong ongoing intellectual challenges to the Chief Engineer and the Core Team. In order to lead and manage these challenges, the best engineers should be properly groomed for the position of Chief Engineer, as listed in Box 8.

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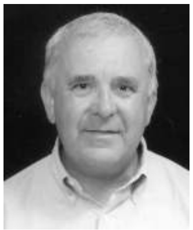

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