LEAN ADVANCEMENT INITIATIVE ™

Lean Product Development in the Aerospace Enterprise

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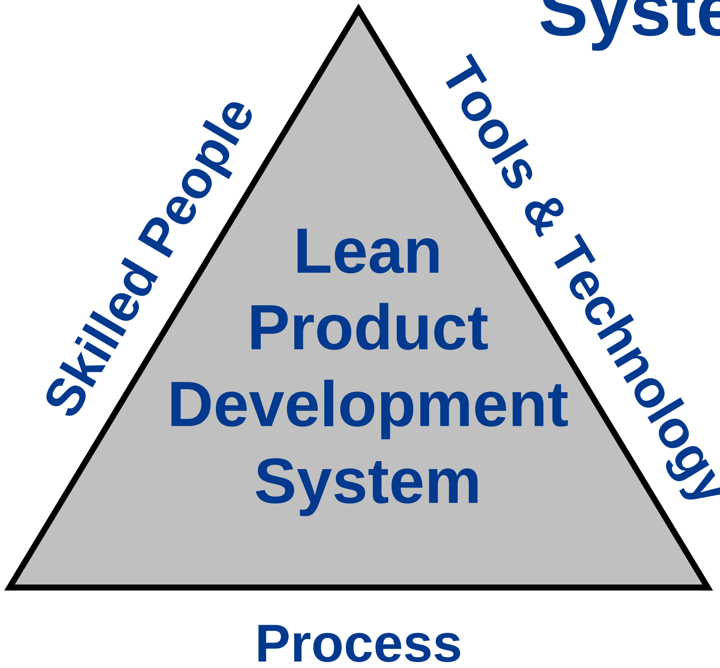
Lean Product Development (PD) Background

- **Diverse perspectives:**
  - **PD system modeled after Toyota's (e.g., Morgan and Liker, 2007; Liker, 2004; Fujimoto, 2001; Kennedy, 2004; Ward, 2008)**
  - **Streamlined processes (e.g., McManus, 2004; Locher, 2008)**
  - **A set of tools adapted from Toyota manufacturing (a long list…)**
  - **Hybrids or complimentary methods (e.g, Lean Systems Engineering—Rebentisch, et al, 2004; Design for Six Sigma—Yang et al, 2008)**
  - **A "Lean" product (e.g., Boothroyd, et al 2001; Miles, 1972)**
- **Lean PD is in its earliest stages of evolution and application in aerospace PD**
- **Central issues for Lean PD in Aerospace:**
  - **Large lifecycle cost "tail" for the system defined in product development**
  - **Severe demands for quality, safety, reliability in challenging operating environments**
  - **Complex-system interdependencies and failures**
  - **High requirements novelty**

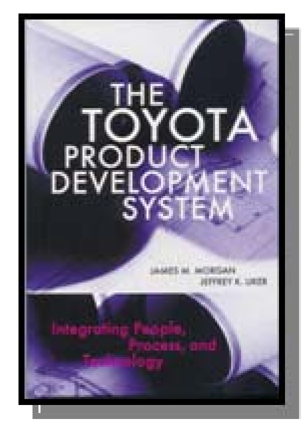
A Suitable Product Development System Framework?

5. Develop a Chief Engineer System to Integrate Development from Start to Finish
6. Organize to Balance Functional Expertise and Cross-functional Integration
7. Develop Towering Technical Competence in all Engineers
8. Fully Integrate Suppliers into the Product Development Systems
9. Build in Learning and Continuous Improvement
10. Build a Culture to Support Excellence and Relentless Improvement



11. Adapt Technology to Fit People and Processes
12. Align your Organization through Simple Communication
13. Use Powerful Tools for Standardization and Organizational Learning

1. Establish Customer-Defined Value to Separate Value-Added from Waste
2. Front-Load the Product Development Process to Explore Thoroughly Alternative Solutions while there is Maximum Design Space
3. Create a Leveled Product Development Process Flow
4. Utilize Rigorous Standardization to Reduce Variation, and Create Flexibility and Predictable Outcome



Source: Morgan & Liker, 2006

Research Objectives

- Develop framework to describe lean PD system attributes and evolutionary pathways in complex product environments
- Provide PD system managers insights for future improvements and progress assessment
- Draw on a diverse array of research and implementation knowledge resources
  - Books, journal articles, student thesis research, case studies, benchmarking exercises, application experience
- Not to create a list of lean tools
  - The two are not incompatible, and the list will likely emerge anyway
- Caveat: this is a preliminary report of research progress

Framework for Phases of Lean PD System Evolution

Emergent

Motivations: Problem-solving (e.g., cure programs, cut costs)
Change Orientation: Reliance primarily on expert change agents (many external)

Maturing

Motivations: Changing system behaviors (e.g., address fundamental changes in resources, relationships)
Change Orientation: Emphasis on development of all employees as change agents; top-down, middle-across, bottom-up system change

Accelerating

Motivations: expand system capabilities for growth (e.g., high throughput, market expansion)
Change Orientation: Expand/exploit capacity/ capabilities across enterprise and extended enterprise network (e.g., partners/suppliers)

Emergent Phase

Emergent

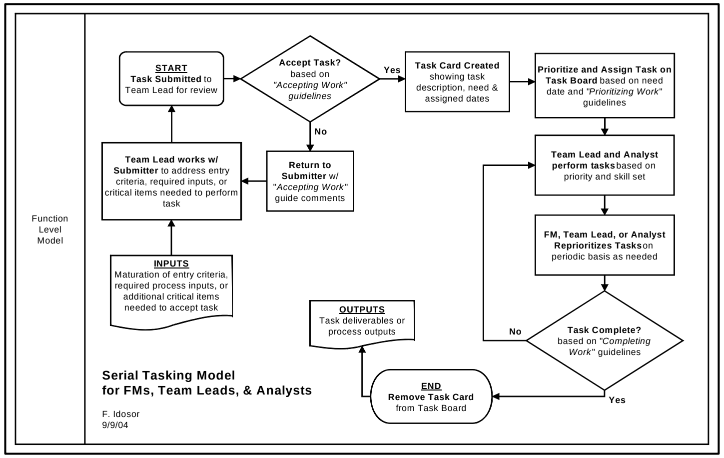
Motivations: Problem-solving (e.g., cure programs, cut costs)
Change Orientation: Reliance primarily on expert change agents (many external)

- **Primary Focus: Eliminate waste, deliver value to the customer, deliver savings from improved performance back to the organization**
- **Imperative: Expand (both number and scope of) activities driven by value-oriented philosophy**
  - **Early: Map value streams, eliminate wasteful behaviors, fix operating problems**
  - **Maturing: develop sophisticated understanding of customer value and permeate it throughout the organization's value stream**

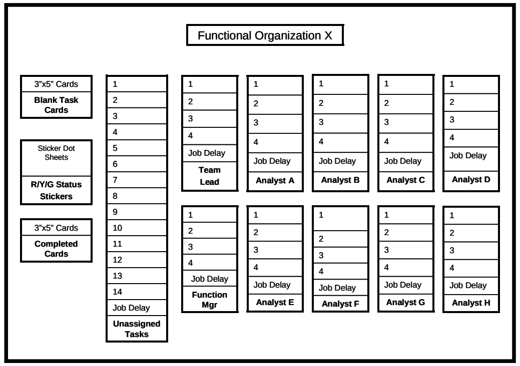
Evidence

- **Simple tools lower barriers to experimenting with Lean and achieving compelling results in PD-related processes:**
  - **23% savings from improved document review & approval and search & retrieval (Lawia and Williams, 2004)**
  - **35 day schedule reduction in turbine test cell throughput (Kraft, 2004)**
  - **28% schedule reduction from RFP to contract and 63% reduction in change process time (Jobo, 2004)**
  - **53% reduction in engineering and contract change process cycle time (Davis 2008)**
- **Quick benefits not surprising given the amount of wasted effort in information-intensive processes**
  - **A study of 2 design teams found that only 12% of information transfer effort provides value to the end user, with almost 50% pure waste (Graebsch, 2005) Very similar to McManus' findings (2004) from a different population.**
  - **A study of 3 software development teams found that rework grew exponentially as time passed without the problem being solved. It was found that information inventory loses its value in storage at 6% per month (Kato, 2005)**
- **Deploying a clearer understanding of user value across the organization can improve outcomes**
  - **Use of boundary objects, system representations, integrated cost models (Carlile, et al, 2003; Dare 2003; Cowap, 1998) to communicate users' values improve program outcomes significantly**

Example: PD Flow Line Enabled by Streamlined Processes and Standard Tasks

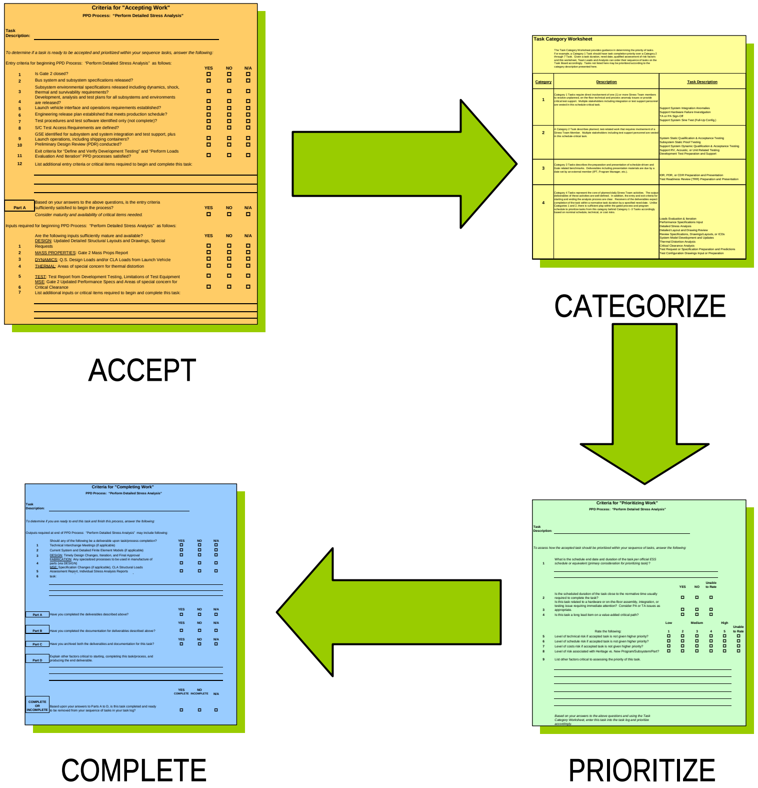


Serial-Tasking Flow



Visual task board enables workflow pull

Desktop instructions guide serial task flow



Eliminates multi-tasking waste and cuts workflow cycle time.

Source: Idosor et al (2006)

Observations About the Emergent Phase

- First step in eliminating waste is identifying value
  - Less obvious: a common definition of value is critical to unifying the efforts of a diverse set of enterprise PD stakeholders
- Typical countermeasures:
  - “Kaizen” events, DFSS projects, improvement events early on
  - Local alignment efforts (IPTs, project teams)
  - Alignment tools (integrated design environments, common models)
  - Critical: leadership emphasis on customer value across team
- Areas for focus through the emergent phase:
  - Value stream knowledge and mastery through continuous mapping and analysis
  - PD leaders focus enterprise on value creation and waste reduction through plans, policies, and structures
  - Extensive customer knowledge and well-defined processes create clear product vision and objectives
  - Create mechanisms and processes to enable value-based tradeoff decisions across organizational boundaries

Maturing Phase

Maturing

Motivations: Changing system behaviors (e.g., address fundamental changes in resources, relationships)
Change Orientation: Emphasis on development of all employees as change agents; top-down, middle-across, bottom-up system change

- **Primary Focus: Develop capabilities and capacity to address system-level inefficiencies or waste**
- **Imperative: Enterprise-wide product and process quality orientation and process improvement capabilities**
  - **Early: process documentation and standardization**
  - **Maturing: routine and automatic process analysis and improvement and all levels of the organization**
  - **Transition from open- to closed-loop problem-solving and organizational learning as the norm of operations**

Evidence

- Study of 2 teams found project information tools (common databases and applications, virtual presence) indispensible to program execution, with a healthy ROI of >3000% (Taylor, 2005)
  - Reduction in process cycle times (46% of benefit)
  - Reduction in process re-work waste (33% of benefit)
  - Reduction in travel expenses (22% of benefit)
- But, in a study of 4 programs (two from the 1970s, two from the 1990s), the earlier programs outperformed the modern programs in both vehicle and programmatic outcomes (less post-design rework, better control of trends)
  - Modern tools were deemed essential to execution, but deficiencies in workforce skills and capabilities resulted in poorer performance (Andrew, 2001)
- Development of Engineering Standard Work at Pratt & Whitney Aircraft Engines was a response to significant loss of staff and knowledge in the 1990s (Bowen, et al 2006)

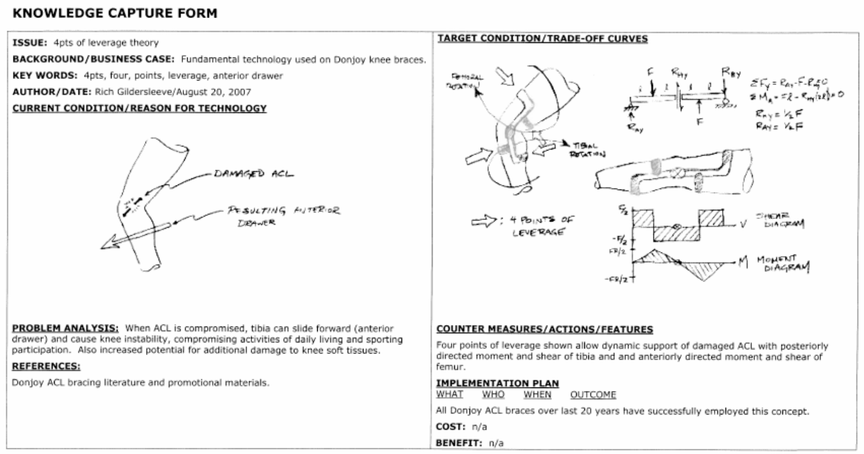
Standardized Work at Individual and Team Levels

- Standard work allows experimentation and continuous process improvement
  - e.g., “DNA” of Toyota, “LAMDA” method
- Engineering Standard Work (ESW) at Pratt and Whitney:
  - Workflow maps (flows, swimlanes, dependencies)
  - Activity description (task description, work instructions, tools, SIPOC)
  - Tools and methods (validated tools with range of applicability, instructions)
  - Design criteria (intent and basis for specifics)
  - Design standards (preferred configurations and processes)
  - Lessons Learned (revisions to methods, history, performance)
  - Practitioner capabilities (assess ability of engineers to perform standard work without supervision or review)
- Generic elements:
  - Standard tools, cycle times, performance expectations
  - Skills-based personnel progression system
  - Process owner responsibility for continuous improvement

From Bowen, et al (2006)

Effective Knowledge Capture Enables Reuse and Closed-loop Learning

- **Key element of standard work**
- **Domain expert is owner**
- **Keep it simple/usable**
- **Define:**
  - **Part performance over a range**
  - **Performance limitations**
  - **Failure modes with root causes and countermeasures**
  - **Graphical display is better**
- **Simplify and update continuously**
- **Benefits from product standard architecture**



KNOWLEDGE CAPTURE FORM

ISSUE: 4pts of leverage theory

BACKGROUND/BUSINESS CASE: Fundamental technology used on Donjoy knee braces.

KEY WORDS: 4pts, four, points, leverage, anterior drawer

AUTHOR/DATE: Rich Gildersleeve/August 20, 2007

CURRENT CONDITION/REASON FOR TECHNOLOGY

PROBLEM ANALYSIS: When ACL is compromised, tibia can slide forward (anterior drawer) and cause knee instability, compromising activities of daily living and sporting participation. Also increased potential for additional damage to knee soft tissues.

REFERENCES:

Donjoy ACL bracing literature and promotional materials.

TARGET CONDITION/TRADE-OFF CURVES

COUNTER MEASURES/ACTIONS/FEATURES

Four points of leverage shown allow dynamic support of damaged ACL with posteriorly directed moment and shear of tibia and and anteriorly directed moment and shear of femur.

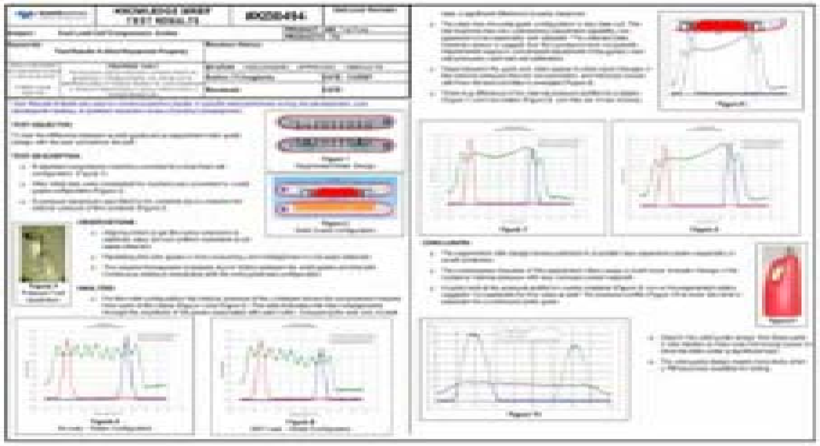
IMPLEMENTATION PLAN

WHAT WHO WHEN OUTCOME

All Donjoy ACL braces over last 20 years have successfully employed this concept.

COST: n/a

BENEFIT: n/a



Source: Ward (2007); Images from Marsiglio (2008), Gildersleeve (2008)

Observations About the Maturing Phase

- **The capacity of the system to continuously learn may quickly be limited by people and organizational dynamics**
  - **Lean improvement journey unfolds over years (decades)**
  - **Lean-enabled growth may outpace supply of experienced employees, coaches, and leaders, leading to unsustainable improvement**
- **Typical countermeasures:**
  - **“Quality” emphasis across the organization—do the job right each time**
  - **Employee training and development a cardinal principle of learning systems (e.g, Deming’s principles, mentorship process at Toyota, etc.)**
    - **High fraction of regular workforce participation in using standard work and root cause analysis to instill a culture of personal accountability for continuous improvement**
  - **X% of workforce certified (e.g., proficiency levels, belts, etc.)—constant advancement, replenishment, and skills growth process**
  - **Organization leadership must establish and exemplify (e.g., lead by teaching) a climate of engagement and learning**
- **Areas for focus through the maturing phase:**
  - **Establish quality targets and build performance assessments into work processes to provide immediate feedback on outcomes**
  - **Level work load, prevent overburden of resources (static and transient) to enable learning and continuous improvement of processes and handoffs**
  - **Maintain full pipeline of skilled staff, teachers, and leaders (both core technical and continuous improvement skills)**

Accelerating Phase

Accelerating

Motivations: expand system capabilities for growth (e.g., high throughput, market expansion) building on continuous improvement gains
Change Orientation: Expand/exploit capacity/ capabilities across enterprise and extended enterprise network (e.g., partners/suppliers)

- **Primary Focus: Seamless integration and execution across the value stream**
- **Imperative: Leverage extended enterprise capabilities to create sustained organic growth and expand to new business lines**
  - **Early: flow/pull processes ensure seamless operations**
  - **Maturing: fully capable supplier partners provide excess capacity and prevent perturbations from disrupting enterprise growth and learning processes**
  - **Continuous improvement is an institutionalized part of the business operating system**

Evidence

- No real enterprise-level examples from aerospace (yet)
  - F/A-18E/F *program* enterprise exhibits a number of traits of an organization transitioning through the Maturing/Accelerating phases, but this framework emphasizes lean transformation progress in the multi-program enterprise
  - Concepts to populate this section drawn by analogy from Toyota PD practice
- Toyota analogies
  - Standard product architecture enables knowledge reuse
  - Set-based concurrent engineering reduces integration risk earlier in program by exercising more learning opportunities
  - Exhaustively manage the interdependencies and handoffs across the organization
    - Extensive integrating roles and functions reduce misalignment and poorly-executed handoffs
  - Suppliers evolve towards full participation in knowledge-intensive processes

Use Product Architecting Process to Increase PD Learning Cycles

- Product novelty consumes PD system capacity and undermines generalizable knowledge from experiment-based problem-solving
  - Standard product architectures greatly reduce risk, cycle time, and resources required per product offering
- Examples:
  - Derivatives typically require a fraction (e.g., 0.25-0.35 in a study of multiple organizations) of the resources of the development of the original platform (Beckert, 2000)
  - 25-50% savings from subsystem commonality in both development and operations (Nuffort, 2001)
- Areas for emphasis:
  - Increase reuse of product artifacts, standardization, system integration understanding
  - Enable knowledge capture and process refinement
  - Use tradespace exploration as an opportunity to develop deeper understanding and knowledge about elements within the architecture (e.g., refine tradeoff curves) and system interdependencies

Set-Based Concurrent Engineering

- **The Toyota Product Development System (TPDS) uses Set-Based Concurrent Engineering to both make preliminary design choices and refine designs to completion**
- **Basic idea is to *delay* decisions, carrying multiple designs forward where practical. Timing is an important factor:**
  - **Chassis decision made on decade-long cycle; Muffler decisions made in test lot *after* full-scale production has started**
- **Set-Based design complements trade-space understanding - keep options open in areas of high risk and/or low cost**
  - **In TPDS, Chief Engineer owns the "trade-space" knowledge**
- **Highly dependent upon mastering individual elements of the tradespace (understand especially challenging areas)**
  - **Engineering functions create/update the "notebooks" that map the territory**
  - **Modular architecture (independence of functions) is the context for this activity**

Source: Ward (2007)

Mind the Gap: Planning Handoffs Prevents Missteps During Execution

- Stable operations facilitate learning, process refinement, and organic growth of capabilities
  - Appropriate the payoff from the development of standard work and other formalized and improved processes
- Examples:
  - Toyota Hoshin Kanri planning
- Areas for emphasis:
  - Focus on creating and measuring consistent hand-offs across processes
  - Enable cadence in process execution and integration cycles
  - Create periodic integrating events/mechanisms/roles for project-level coordination
  - Manage product pipeline and portfolio to ensure level loading of resources

Toyota Chief Engineer

- The chief engineer (CE) is an entrepreneurial position in a large bureaucratic organization.
  - The "Heavyweight Program Manager"—a super-engineer AND leader
  - The most admired position within Toyota, even more than a director or vice-president
- The CE is the person responsible to senior management for the success of a new product line, and for ensuring value delivery to the customer.
  - Focuses on integration across disciplines and functions
  - Does not have formal authority over the engineers working on the program but has ultimate responsibility for the success of the design, development, and sale of the car
- Is responsible for:
  - Overseeing design projects
  - Making sure they are on time, on budget
- Ultimate responsibility:
  - Delivering value to the customer

Source: Morgan & Liker, 2006

TPDS Chief Engineer, Cont.

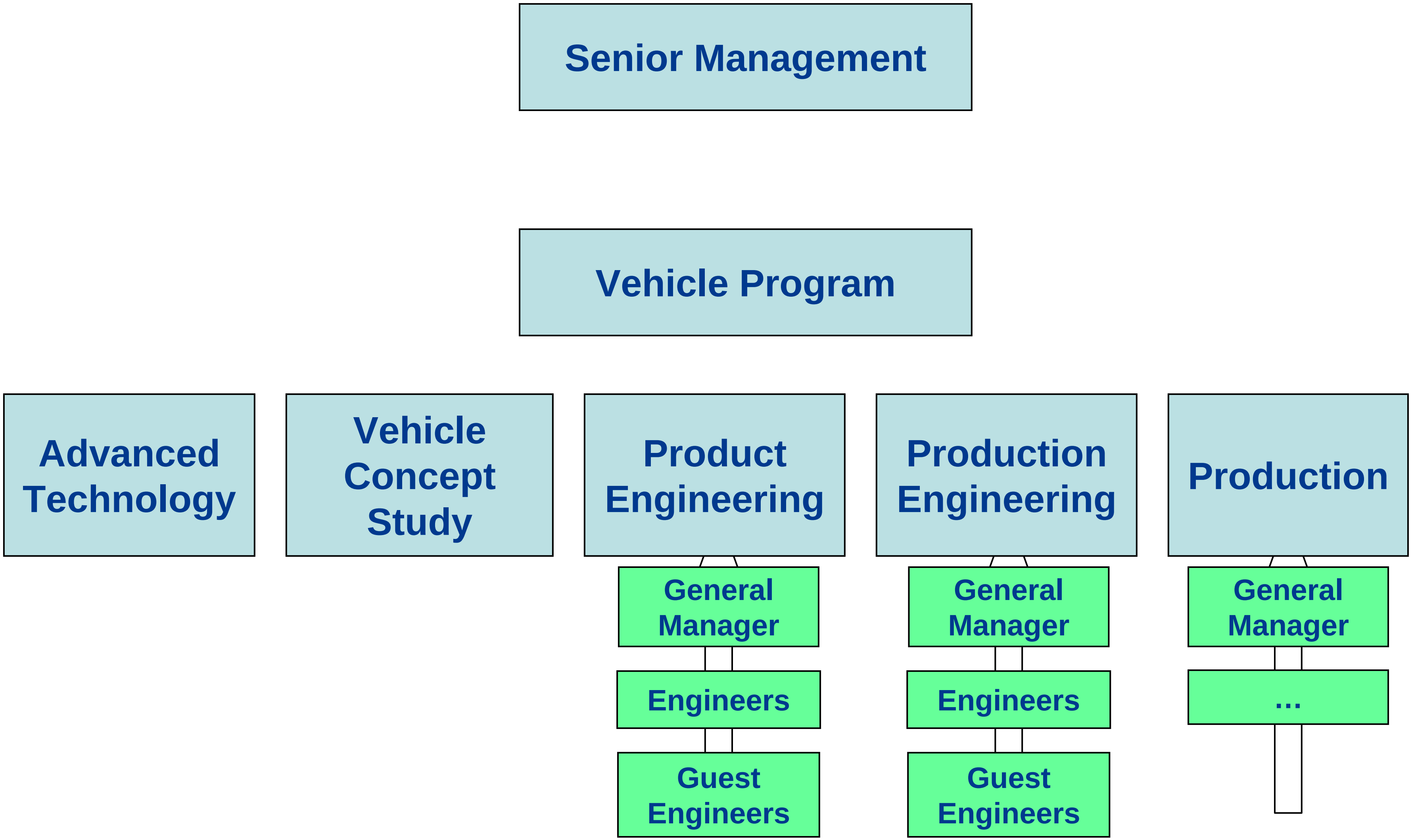
- **CE originally used in the aeronautics sector but adopted by Toyota**
- **Characteristics valued in a CE:**
  - **visceral feel for what customers want**
  - **exceptional engineering skills**
  - **intuitive yet grounded in facts**
  - **innovative yet skeptical of unproven technology**
  - **visionary yet practical**
  - **hard-driving teacher, motivator, and disciplinarian, yet a patient listener**
  - **no compromise attitude to achieving breakthrough targets**
  - **exceptional communicator**
  - **always ready to get his or her hands dirty**

Source: Morgan & Liker, 2006

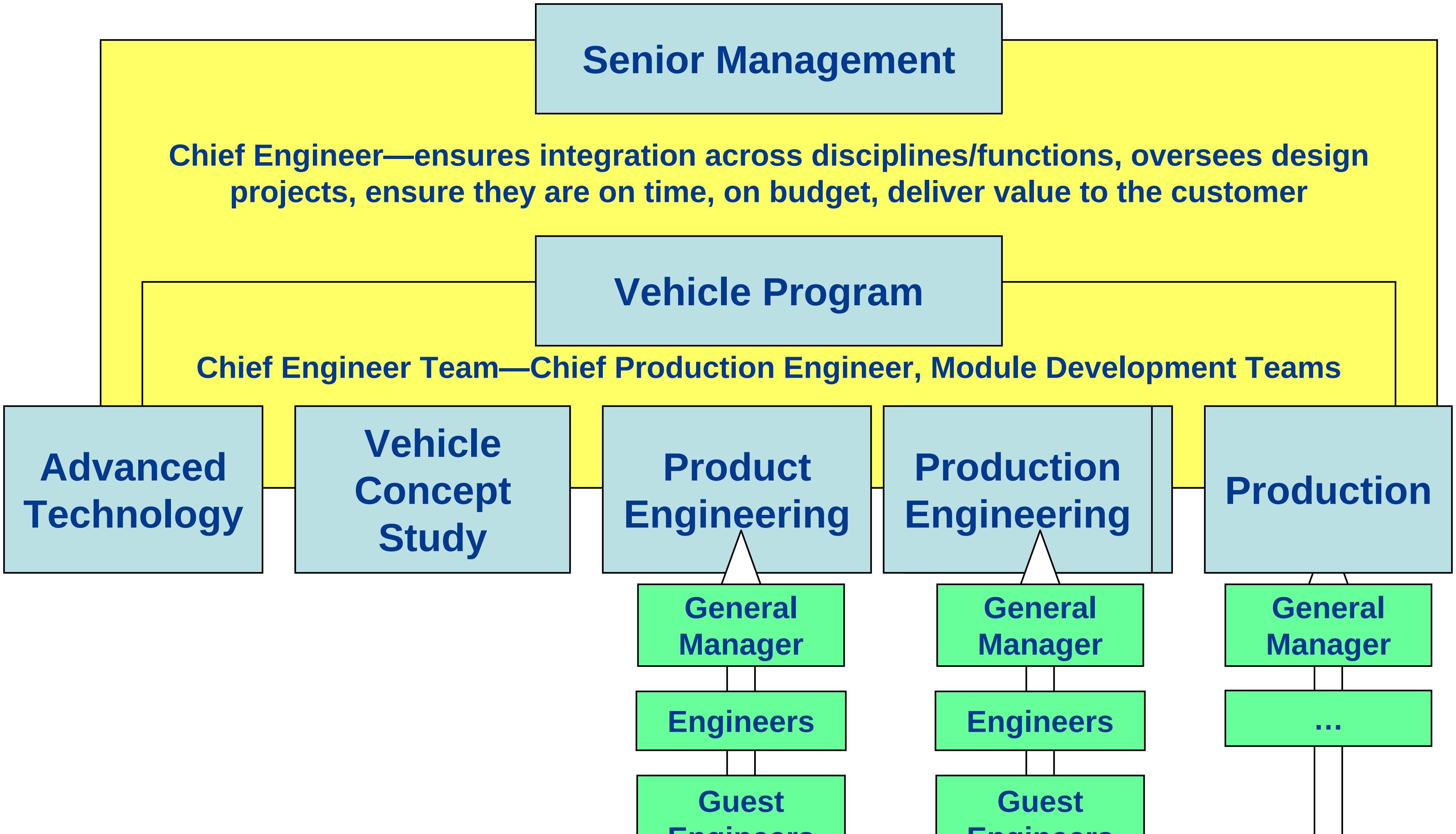
Multiple Redundant Boundary-Spanning Roles Enable Seamless PD Workflow

- TPDS Module Development Teams (MDTs)
  - Organized around vehicle subsystems—identify potential technical problems during the study phase with focus is on the interfaces and map out strategies to minimize deviations during execution. Members of MDT are Toyota's best and seasoned engineers from the product development and production organizations.
- TPDS Simultaneous Engineers (SEs)
  - SEs work to minimize disruption in production startup by taking responsibility for specific parts manufacturability during the study phase. SEs are program-dedicated representatives from production engineering.
- TPDS Chief Production Engineer (CPE)
  - CPE is responsible for overall production preparation and launch for each vehicle program and for transferring production equipment to new facilities. Coordinates all activities of SEs across the MDTs
- TPDS Production Engineers (PEs)
  - PEs are senior production engineers who represent their production areas on the MDTs and provide production liason and knowledge during design phase
- TPDS Advanced Engineer
  - Advanced engineers are relatively autonomous (closely aligned with vehicle centers) and are focused on bringing new technologies to the CE for use in a new vehicle program ("stocking the shelves“)
- Guest engineer or Resident engineer
  - Guest engineers are engineers from suppliers, residing full time in Toyota's PD office create capacity buffers for Toyota product development by transferring its knowledge, skillsets, and routines to partner organizations

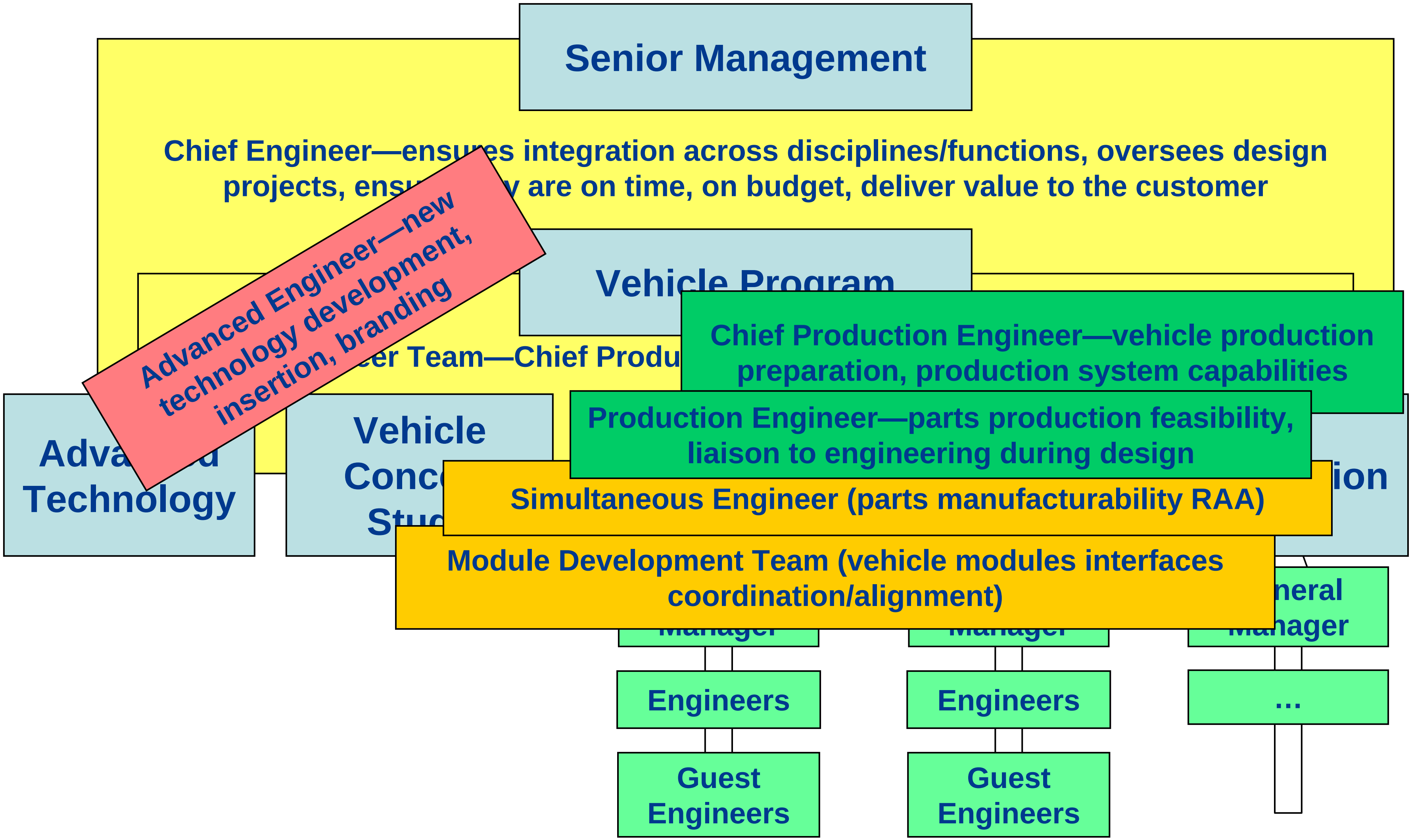
Multiple Stakeholders in the Toyota PD Value Stream



Chief Engineer (CE) and CE Team Coordinate Overall Vehicle PD Value Delivery



Multiple Overlapping Toyota PD System Roles Help Ensure Smooth Handoffs



Expand Tiers of the Value Stream Participating Closely in PD Process

- Suppliers/partners typically represent a major fraction of the product value, and often contribute critical product features/function
  - Poorly-performing suppliers/partners can become the system constraint
  - Predictably-performing suppliers/partners represent additional system capacity and capabilities
- Examples:
  - Toyota “Black Box” supplier certification
    - Aisin Seiki fire (Nishiguchi, 1998)
  - F119 nozzle, JDAM development (Lucas, 1996)
- Areas for emphasis:
  - Deploy enterprise-standard processes and practices through supplier relationships
  - Engage customers and suppliers in tradespace exploration and requirements specification

Discussion

- End-phase objectives
  - Emergent phase: O(10^1-10^3) improvement “events”/year—high-impact discrete actions, typically expert-lead
    - Much of the US aerospace industry is scattered throughout this phase
  - Maturing phase: O(10^1-10^2) improvement “events”/year *per employee*—more locally focused, lower-impact, driven by individual employees or teams
    - Doesn’t preclude larger projects to enable step-function change in capabilities
    - A few US aerospace organizations are working through this phase
  - Accelerating phase: expand consistency in execution to supplier base, leverage rationalized knowledge/product architecture and lower NRE costs to expand business
    - No clear US aerospace cases identified so far at the multi-program PD enterprise level

Summary

- Roadmap built on observed Lean PD practices in complex product settings (beyond Toyota…)
  - Lack of role model enterprises requires development of a hybrid framework
  - Part of an on-going research study to define the evolution and management of high-performance complex PD systems
- Most US aerospace firms are in the emergent (with some in the early maturing phase)
  - While best-practice programs have been observed for years, consistent enterprise-wide progress is not seen
  - Significant performance variation across programs within the same organization is routinely observed
  - Growth and evolution of capabilities benefits greatly from continuity of leadership and vision
- Lean cases demonstrate measurable and significant program-level performance benefits
  - Many judged to be lean retrospectively