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  - To provide a forum where government, industry, and academia can share lessons learned, promote best practices, address issues, and advocate systems engineering for Systems of Systems (SoS)
  - To identify successful strategies for applying systems engineering principles to systems engineering of SoS
- **Operating Practices**
  - Face to face and virtual SoS Committee meetings are held in conjunction with NDIA SE Division meetings that occur in February, April, June, and August

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- **We will hold all questions until the end:**
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2022 System of Systems Engineering Collaborators Information Exchange Webinars

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May 3, 2022
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May 17, 2022
Mission-Level Optimization: A New Method for Designing Successful Systems
Brian Chell

June 14, 2022
Leverage Set-Based Practices to Make Agile Practices More Effective for System-of-Systems Engineering
Brian Kennedy

June 28, 2022
Model Based Systems Engineering in a Digital Environment: Creating a Virtual Testbed for Complex System Architectures
Claudeliah Roze

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Empowering more

Feature-based Product Line Engineering in Aerospace and Defense

MITRE SoSECIE Webinar

April 19, 2022

Charles Krueger, PhD, CEO

BigLever

onePLE

ISO/IEC 26580

- On April 20, 2021, it became official:
  - ISO/IEC 26580, “Methods and Tools for the Feature-based Approach to Software and Systems Product Line Engineering”, was published as an international standard
  - https://www.iso.org/standard/43139.html
- For the aerospace and defense industry:
  - this powerful engineering approach, created to deliver unprecedented cost avoidance and quality, can now be readily and unambiguously mandated in RFPs and contracts,
  - which can then be unambiguously provided by contractors,
  - leveraging 26580 as the authoritative definition from the international engineering community

Product Line Engineering (PLE) Defined

ISO 26580 Methods and Tools for Feature-based PLE

Product Line:

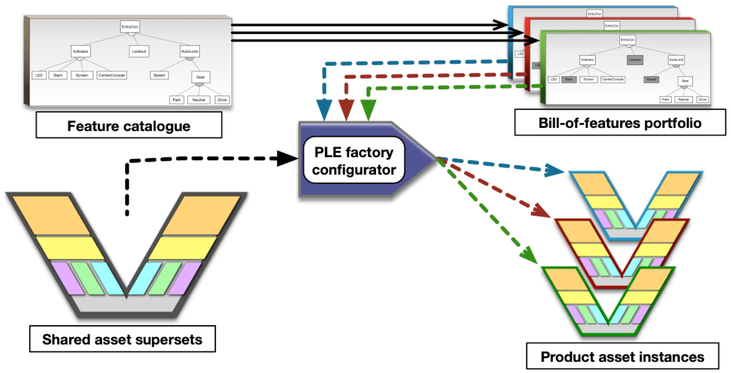
A family of similar products or systems with variations in features.

Product lines are ubiquitous — virtually all products and systems are built in the context of a family.

International Organization for Standardization

Product Line Engineering:

the engineering of a product line using
shared engineering assets,
a *managed catalog of features*, and
an *automated means of production*…

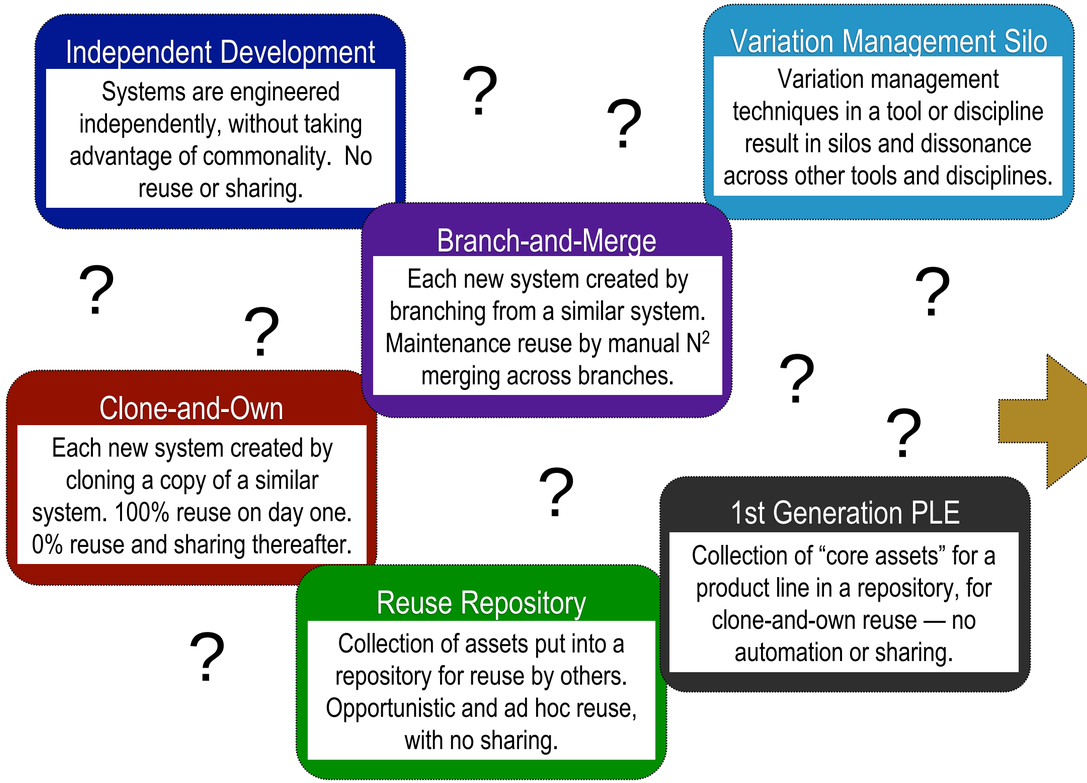


- taking advantage of the **commonality** shared across the family
- efficiently and systematically managing the **variation** among the products or systems

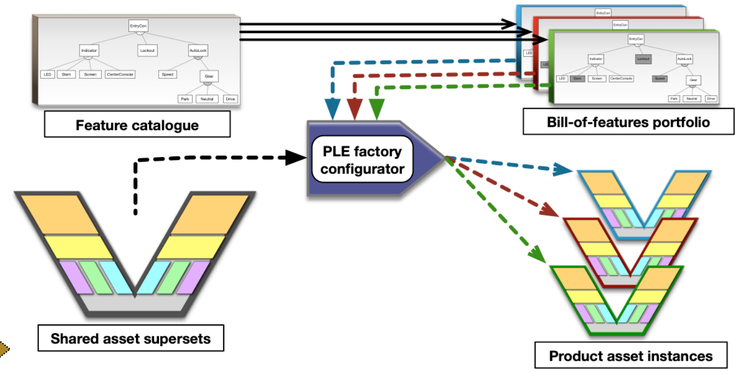
Feature-based PLE is a Paradigm Shift away from Early Generation Complexity

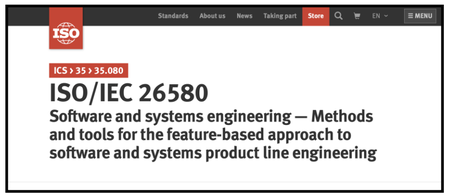
In companies engineering products and systems, the number of product and system configurations is largely viewed as the top and growing source of complexity, which results in one of the top two business challenges, as identified in surveys of nearly 200 company leaders.

Michelle Boucher,
VP of Research for Engineering Practices, Tech-Clarity.
From *Momentum 2021*



Complex Early Generation Product Line Approaches

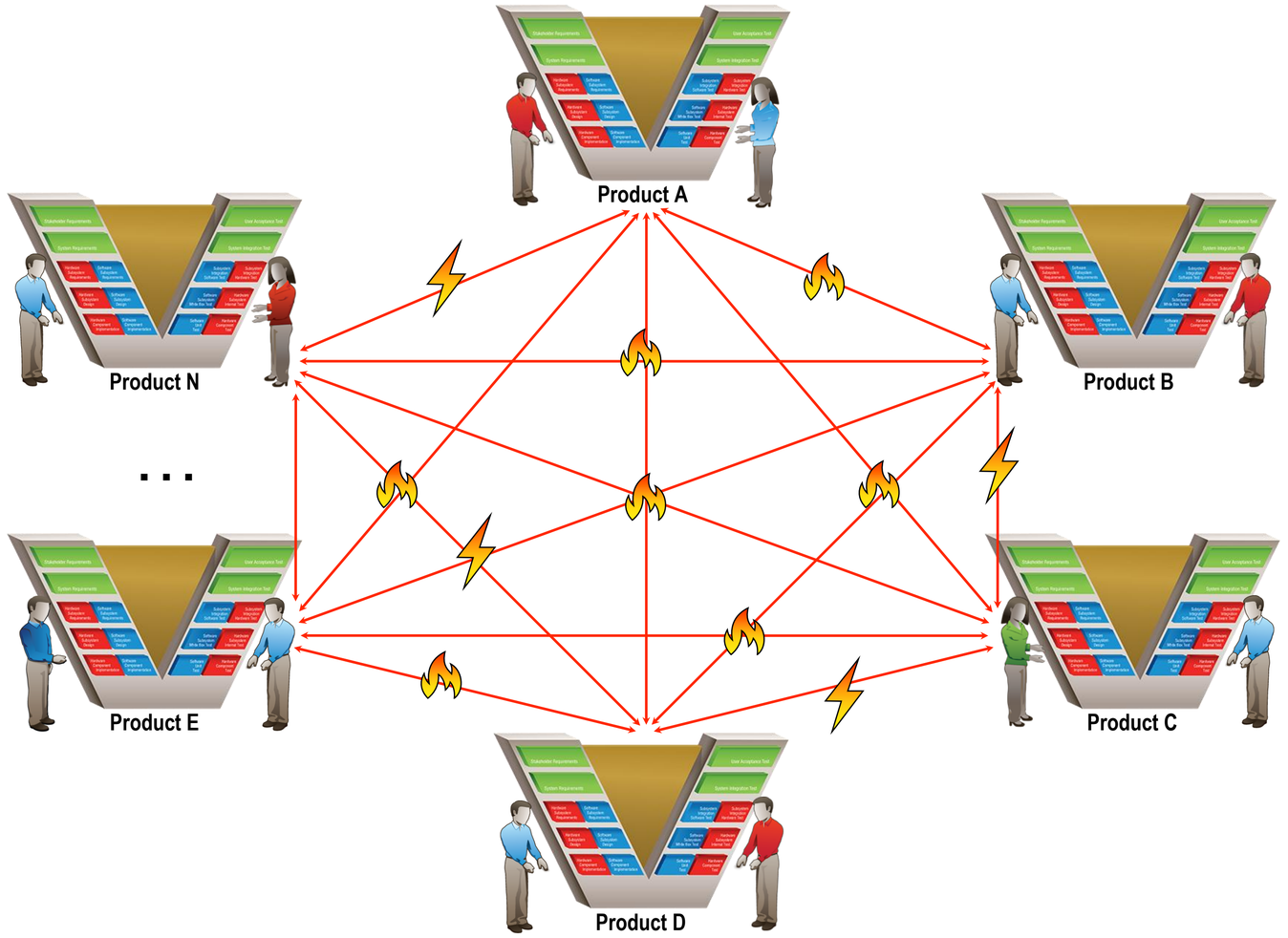




Feature-based Product Line Engineering

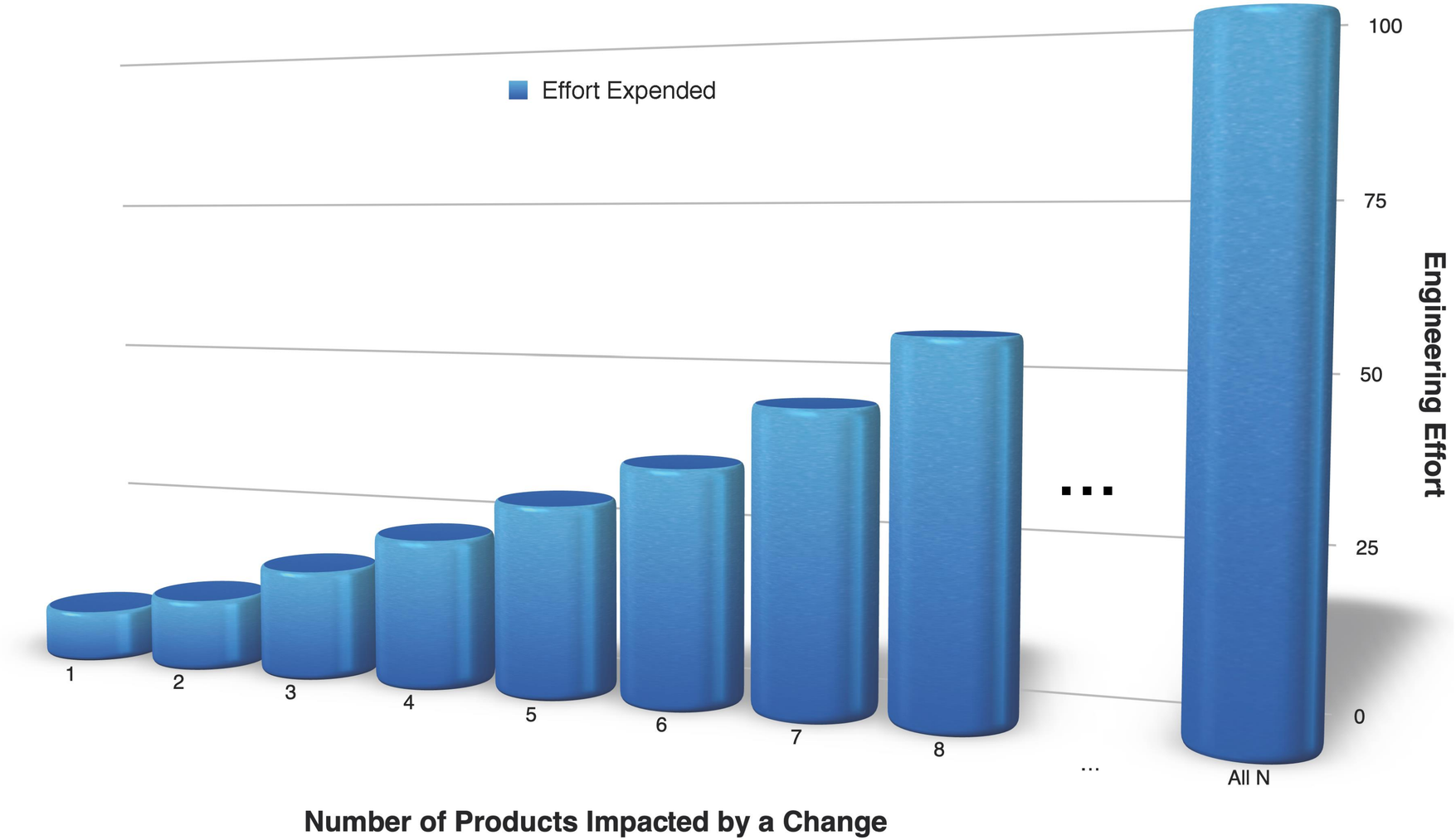
Early Generation Product-centric Engineering

- Duplication, branch-and-merge, clone-and-own, self-inflicted N^2 complexity, …
- Informality introduces significant risks in the form of defects, errors, and omissions
- Leads to delays, budget overruns, recalls, system failures, and opportunity losses



Product-centric Engineering Effort

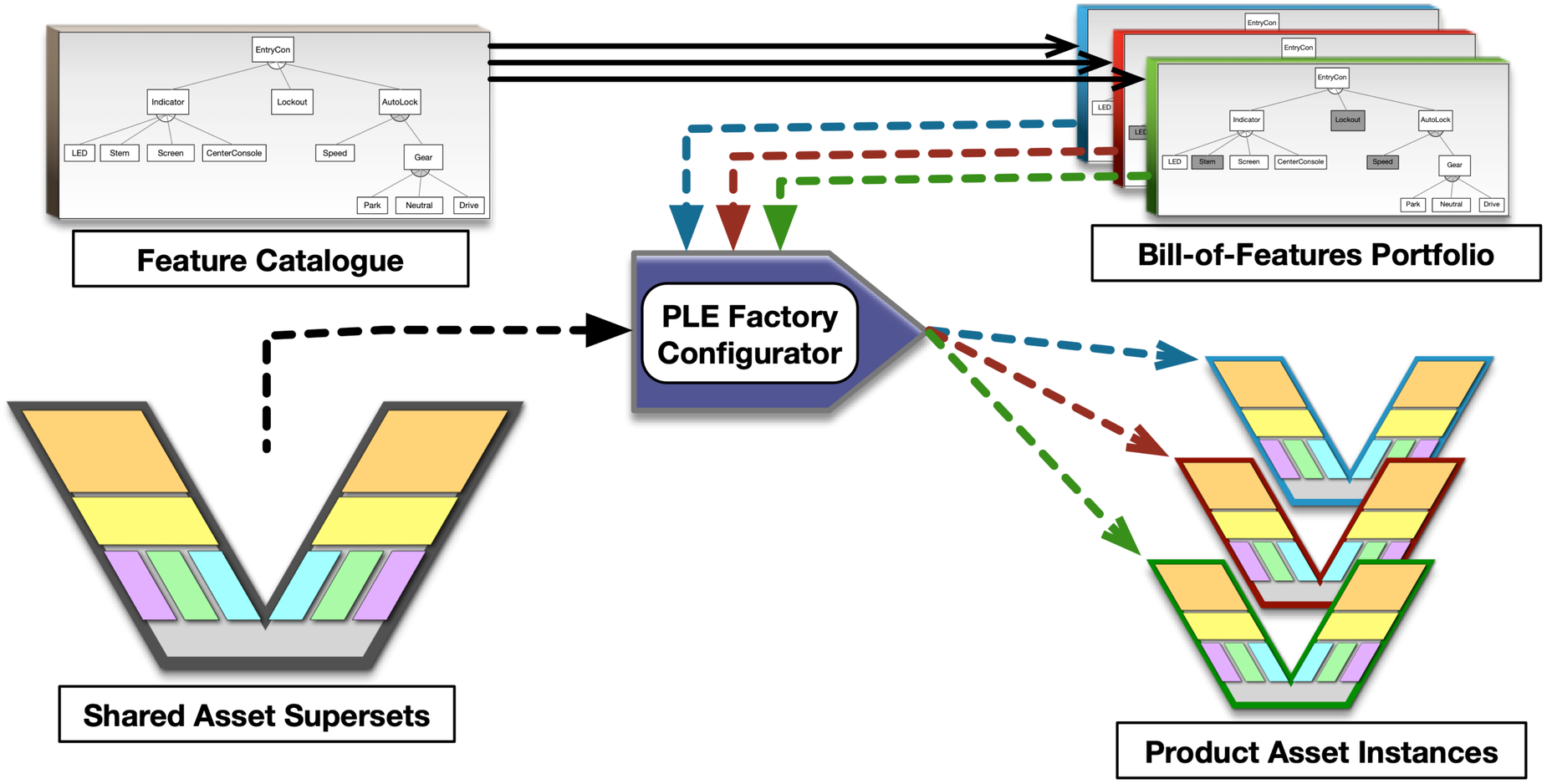
- Dominated by low-value, mundane, replicative work
- Deprives teams of time and energy better spent on high-value innovative work that advances business objectives



Feature-based Product Line Engineering

ISO 26580 Methods and Tools for Feature-based PLE

- Provides a single authoritative source of truth for
  - feature variation
  - engineering assets
- For all products, systems, and subsystems
- For all disciplines



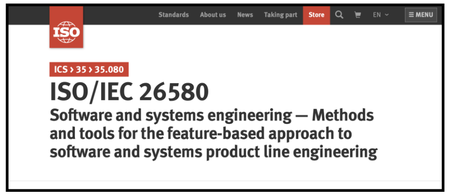


Figure from ISO/IEC 26580
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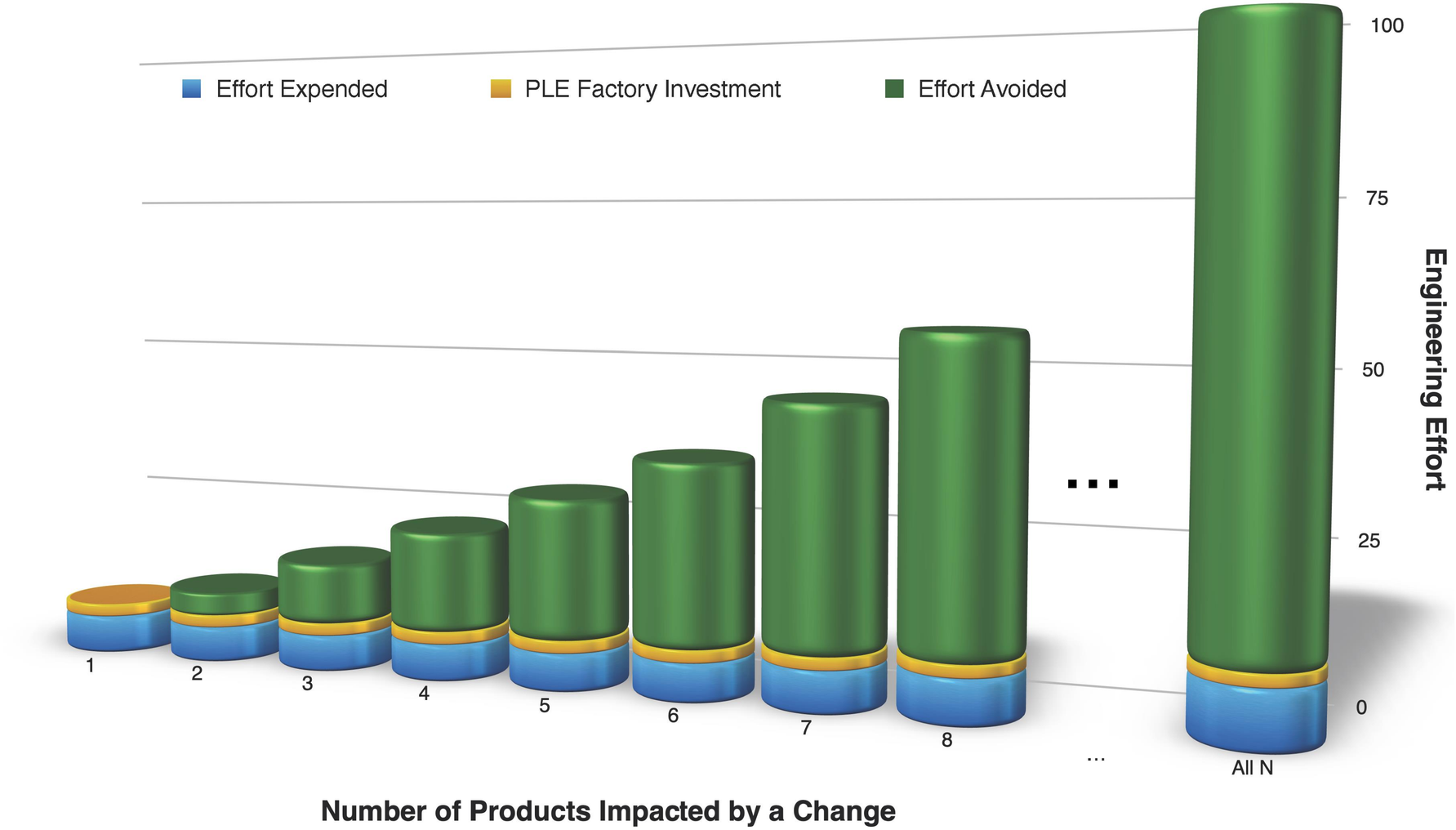
Feature-based PLE Effort Avoidance

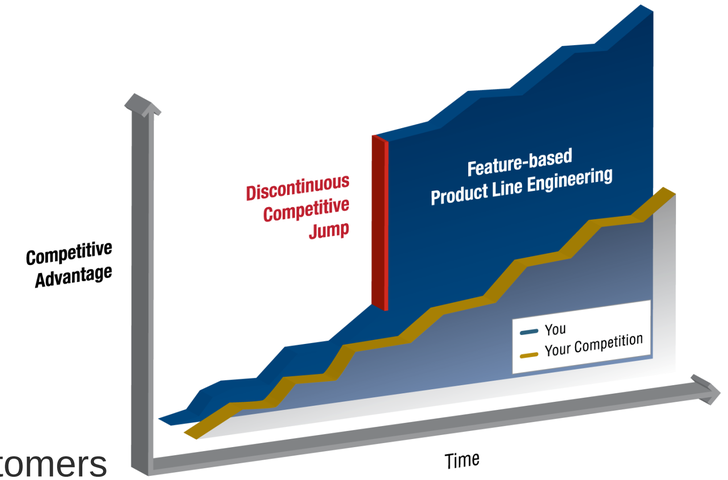
- What if your engineers could do their normal day's work before lunch?
- What would you have them do in the afternoon?



Benefit Hierarchy of Feature-based PLE

Competitive Imperative

Strategic Business Benefits



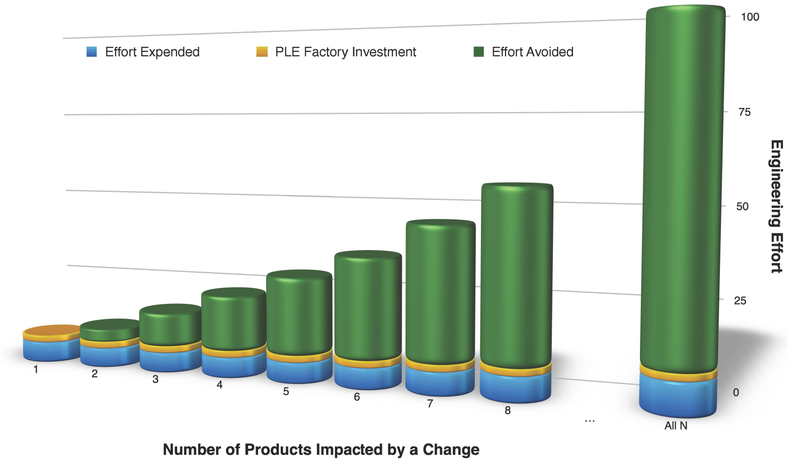
More competitive pricing, more wins, higher sales

Beat competitors to market with new innovations

Higher quality, better reviews, better perception, fewer recalls, happier customers

Higher engineering effectivity mitigates staff retention and hiring challenges

Strategic Engineering Benefits



Higher productivity, shift from low value to high value effort

Higher quality, lower defect density

Faster time to market for new features and new products

Greater scalability of the product line

Root-cause Engineering Effort Avoidance

The ISO/IEC 26580 standard is new, but Feature-based PLE is not

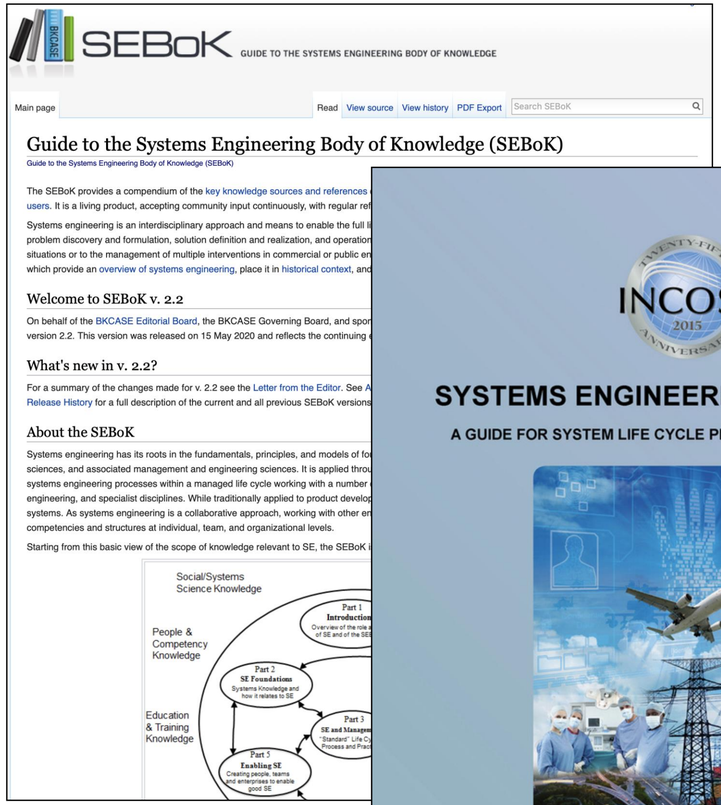
- Although the standard has just been finalized, Feature-based PLE has been in commercial practice in the A&D sector for nearly two decades
  - compiling hundreds of millions of dollars in cost avoidance each and every year
- The approach is being adopted or is already in widespread use by most of the top ten US defense contractors
- Feature-based PLE has earned its stripes by rising to the practicalities and hard challenges that are emblematic of the A&D sector

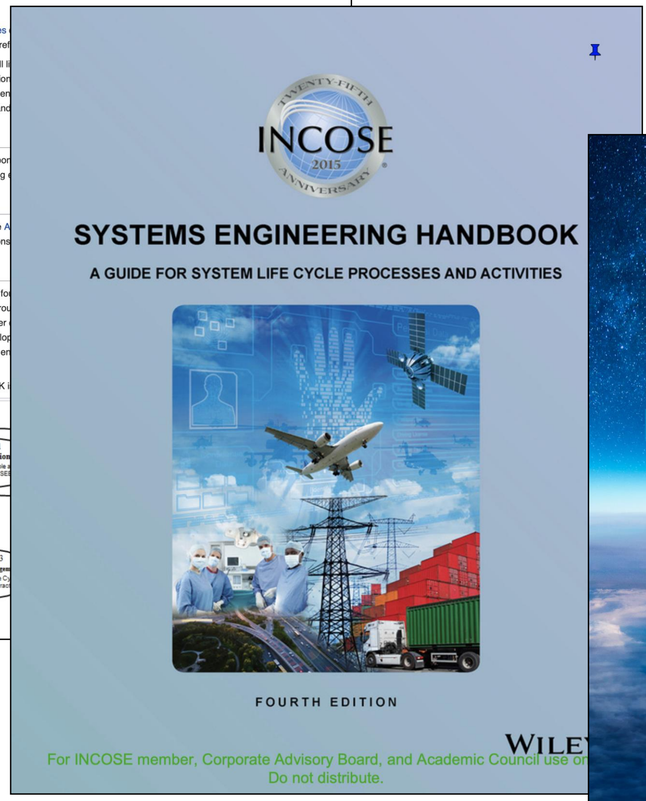
LOCKHEED MARTIN	GENERAL DYNAMICS	gm	Raytheon Technologies	GE Aviation
AEGIS Weapon System for US and International Navies	Live Training Transformation: US Army, Air Force, Marines. Plus enterprise initiative.	One of the largest and most complex product lines, comprising millions of instances per year	Rapidly growing and evolving portfolio of the world's most advanced missile systems	Helicopter engines for all configurations of the new US Army Future Vertical Lift (FVL) program
High cost of old approach threatened loss of entire contract	Innovative low-cost solution essential to win and retain major contracts	Significant challenges to provide suppliers with a family of complex specs for electronic controller unit families	Traditional methods of creating and testing prototypes are too slow, imprecise, expensive to meet mission demands	Demand to maximize sharing and reuse to prevent multiplicative costs for flight certification
Feature-based PLE Results with BigLever				
Turned an at-risk program into an enthusiastic long-term relationship by eliminating low-value redundant effort	**Grew a $2B+ business from scratch with the US DoD. Delivering 3x more capability within budget, to the delight of the customer**	**Digital transformation to a digital supply chain by applying PLE to MBSE**	**Using Feature-based PLE to proliferate best candidate simulations to find optimal solution within a trade space**	**Using a single Feature-based PLE Factory with a single collection of shared engineering assets for the full engineering lifecycle**

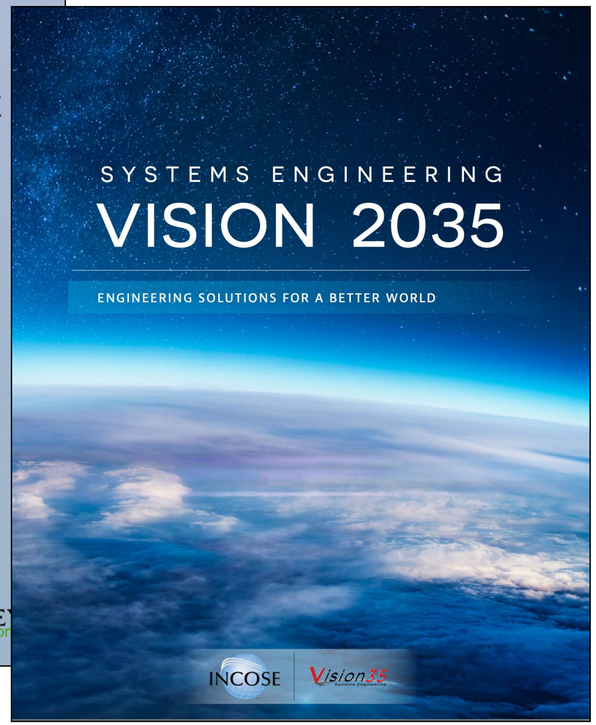
“Change is good. You go first.”

- When it comes to Organizational Change, technology is easy and people are hard
- “Feature-based PLE sounds great, but we’re different — it won’t work here…”
- Engineering organizations are justifiably risk-averse

Lowering the risk of organizational change by elevating Product Line Engineering to a standard practice in the industry

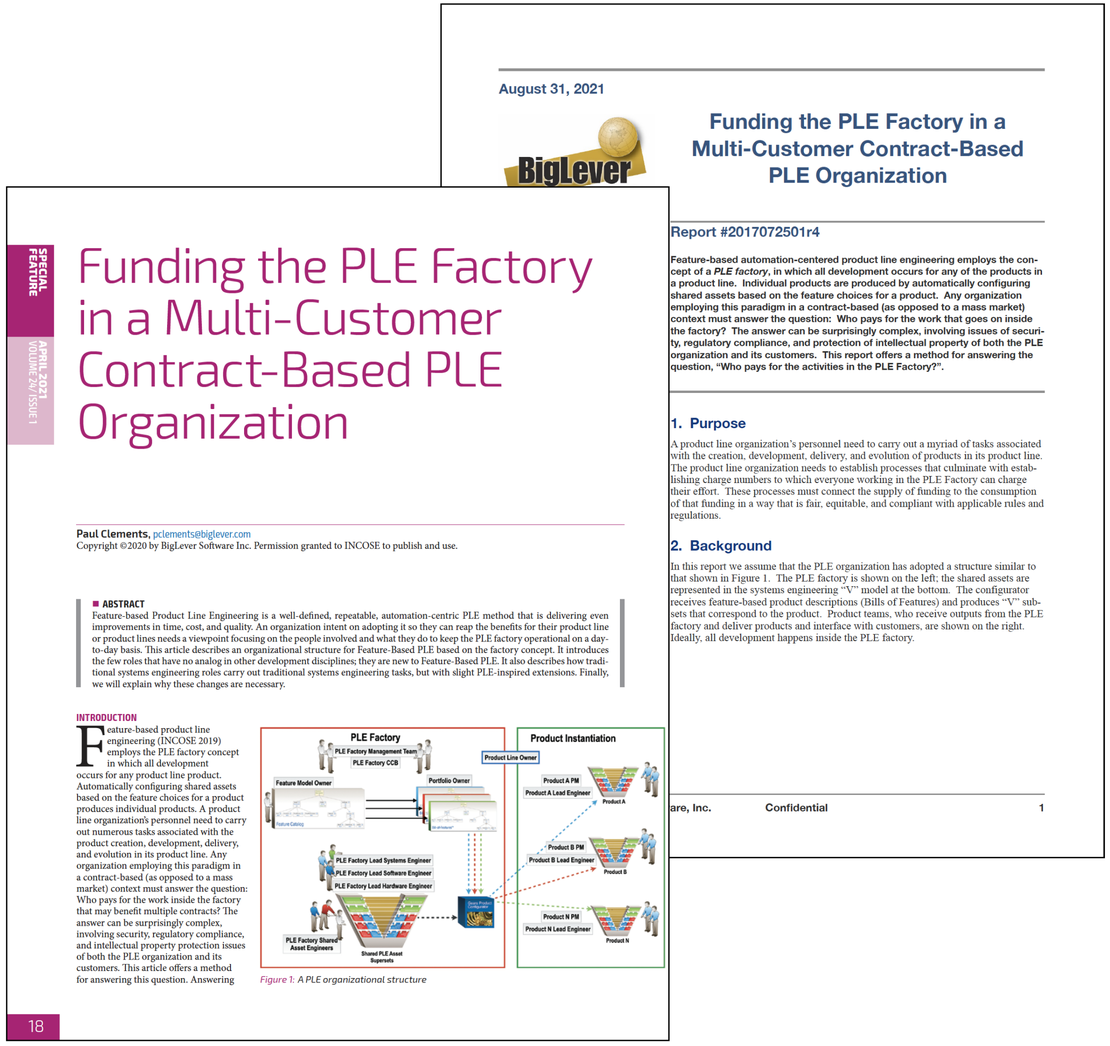






Feature-based PLE in a multi-contract funding context

- In A&D, sharing often needs to occur across programs, contracts, and customers.
- Can that happen? It can.
- Defense companies have worked out methods to pay for activities that benefit more than one program, using an approach that is compliant with acquisition regulations.



August 31, 2021

BigLever

Funding the PLE Factory in a Multi-Customer Contract-Based PLE Organization

Report #2017072501r4

Feature-based automation-centered product line engineering employs the concept of a *PLE factory*, in which all development occurs for any of the products in a product line. Individual products are produced by automatically configuring shared assets based on the feature choices for a product. Any organization employing this paradigm in a contract-based (as opposed to a mass market) context must answer the question: Who pays for the work that goes on inside the factory? The answer can be surprisingly complex, involving issues of security, regulatory compliance, and protection of intellectual property of both the PLE organization and its customers. This report offers a method for answering the question, "Who pays for the activities in the PLE Factory?".

1. Purpose

A product line organization's personnel need to carry out a myriad of tasks associated with the creation, development, delivery, and evolution of products in its product line. The product line organization needs to establish processes that culminate with establishing charge numbers to which everyone working in the PLE Factory can charge their effort. These processes must connect the supply of funding to the consumption of that funding in a way that is fair, equitable, and compliant with applicable rules and regulations.

2. Background

In this report we assume that the PLE organization has adopted a structure similar to that shown in Figure 1. The PLE factory is shown on the left; the shared assets are represented in the systems engineering "V" model at the bottom. The configurator receives feature-based product descriptions (Bills of Features) and produces "V" subsets that correspond to the product. Product teams, who receive outputs from the PLE factory and deliver products and interface with customers, are shown on the right. Ideally, all development happens inside the PLE factory.

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SPECIAL FEATURE

APRIL 2021 VOLUME 24 / ISSUE 1

Funding the PLE Factory in a Multi-Customer Contract-Based PLE Organization

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ABSTRACT

Feature-based Product Line Engineering is a well-defined, repeatable, automation-centric PLE method that is delivering even improvements in time, cost, and quality. An organization intent on adopting it so they can reap the benefits for their product line or product lines needs a viewpoint focusing on the people involved and what they do to keep the PLE factory operational on a day-to-day basis. This article describes an organizational structure for Feature-Based PLE based on the factory concept. It introduces the few roles that have no analog in other development disciplines; they are new to Feature-Based PLE. It also describes how traditional systems engineering roles carry out traditional systems engineering tasks, but with slight PLE-inspired extensions. Finally, we will explain why these changes are necessary.

INTRODUCTION

Feature-based product line engineering (INCOSE 2019) employs the PLE factory concept in which all development occurs for any product line product. Automatically configuring shared assets based on the feature choices for a product produces individual products. A product line organization's personnel need to carry out numerous tasks associated with the product creation, development, delivery, and evolution in its product line. Any organization employing this paradigm in a contract-based (as opposed to a mass market) context must answer the question: Who pays for the work inside the factory that may benefit multiple contracts? The answer can be surprisingly complex, involving security, regulatory compliance, and intellectual property protection issues of both the PLE organization and its customers. This article offers a method for answering this question. Answering

Figure 1: A PLE organizational structure

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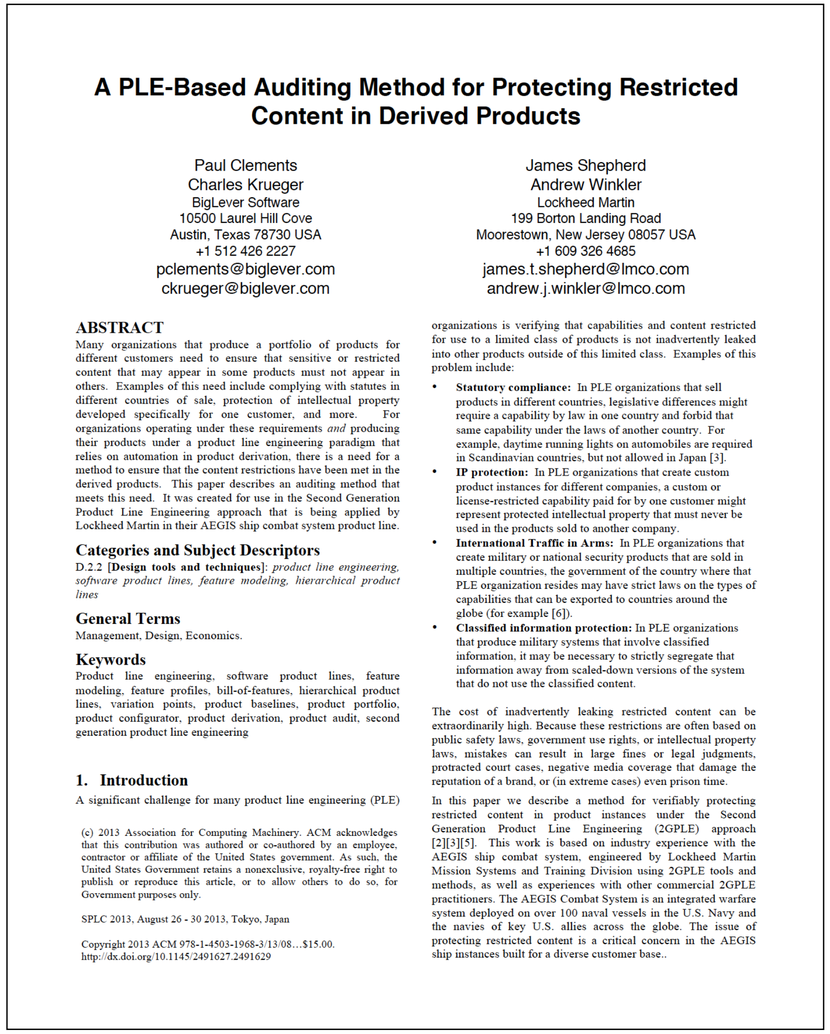
Feature-based PLE and export control compliance

- A product line may have members destined for sale in countries where ITAR or export control restrictions apply.
- Lockheed Martin pioneered a PLE method to ensure that no product contains any content that is not allowed to be exported.



A PLE-Based Auditing Method for Protecting Restricted Content in Derived Products

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ABSTRACT

Many organizations that produce a portfolio of products for different customers need to ensure that sensitive or restricted content that may appear in some products must not appear in others. Examples of this need include complying with statutes in different countries of sale, protection of intellectual property developed specifically for one customer, and more. For organizations operating under these requirements *and* producing their products under a product line engineering paradigm that relies on automation in product derivation, there is a need for a method to ensure that the content restrictions have been met in the derived products. This paper describes an auditing method that meets this need. It was created for use in the Second Generation Product Line Engineering approach that is being applied by Lockheed Martin in their AEGIS ship combat system product line.

Categories and Subject Descriptors

D.2.2 [**Design tools and techniques**]: *product line engineering, software product lines, feature modeling, hierarchical product lines*

General Terms

Management, Design, Economics.

Keywords

Product line engineering, software product lines, feature modeling, feature profiles, bill-of-features, hierarchical product lines, variation points, product baselines, product portfolio, product configurator, product derivation, product audit, second generation product line engineering

1. Introduction

A significant challenge for many product line engineering (PLE) organizations is verifying that capabilities and content restricted for use to a limited class of products is not inadvertently leaked into other products outside of this limited class. Examples of this problem include:

- **Statutory compliance:** In PLE organizations that sell products in different countries, legislative differences might require a capability by law in one country and forbid that same capability under the laws of another country. For example, daytime running lights on automobiles are required in Scandinavian countries, but not allowed in Japan [3].
- **IP protection:** In PLE organizations that create custom product instances for different companies, a custom or license-restricted capability paid for by one customer might represent protected intellectual property that must never be used in the products sold to another company.
- **International Traffic in Arms:** In PLE organizations that create military or national security products that are sold in multiple countries, the government of the country where that PLE organization resides may have strict laws on the types of capabilities that can be exported to countries around the globe (for example [6]).
- **Classified information protection:** In PLE organizations that produce military systems that involve classified information, it may be necessary to strictly segregate that information away from scaled-down versions of the system that do not use the classified content.

The cost of inadvertently leaking restricted content can be extraordinarily high. Because these restrictions are often based on public safety laws, government use rights, or intellectual property laws, mistakes can result in large fines or legal judgments, protracted court cases, negative media coverage that damage the reputation of a brand, or (in extreme cases) even prison time.

In this paper we describe a method for verifiably protecting restricted content in product instances under the Second Generation Product Line Engineering (2GPLE) approach [2][3][5]. This work is based on industry experience with the AEGIS ship combat system, engineered by Lockheed Martin Mission Systems and Training Division using 2GPLE tools and methods, as well as experiences with other commercial 2GPLE practitioners. The AEGIS Combat System is an integrated warfare system deployed on over 100 naval vessels in the U.S. Navy and the navies of key U.S. allies across the globe. The issue of protecting restricted content is a critical concern in the AEGIS ship instances built for a diverse customer base..

SPLC 2013, August 26 - 30 2013, Tokyo, Japan

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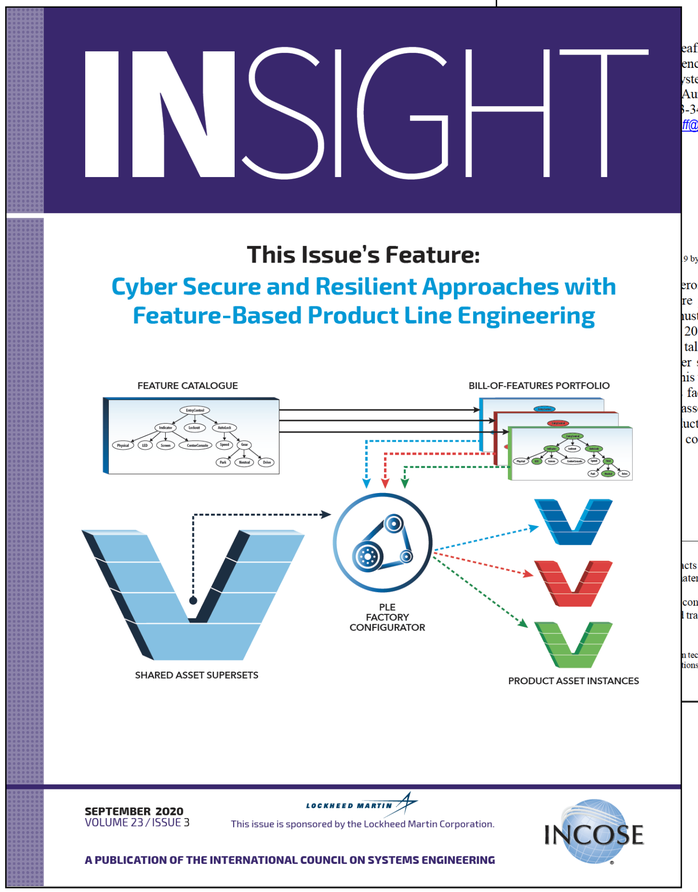
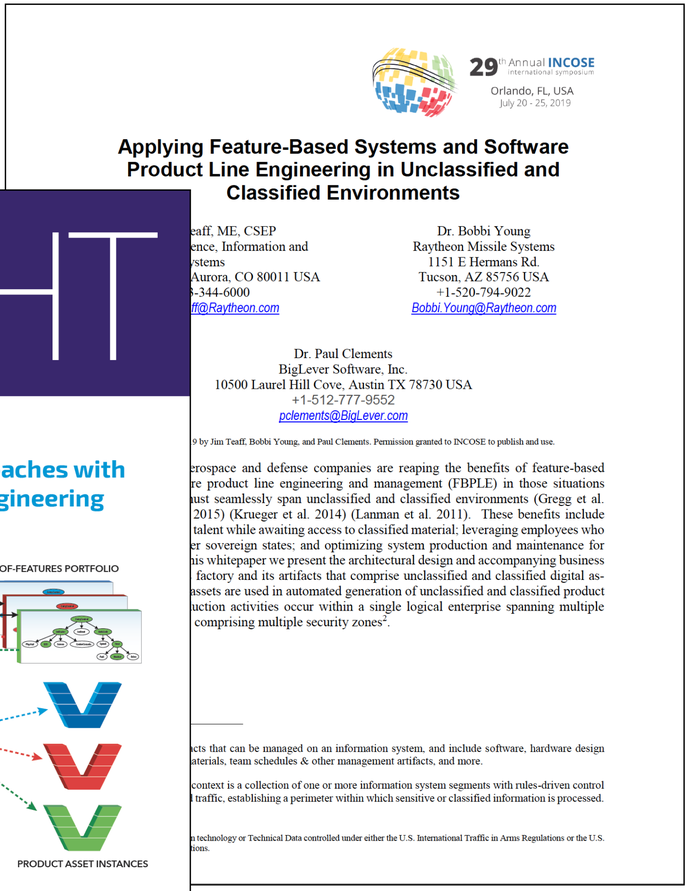
http://dx.doi.org/10.1145/2491627.2491629

Feature-based PLE in security-intensive settings

- Can PLE work in a case where some of the products' content is classified, or classified at higher levels, than other parts?
- Raytheon and General Dynamics have written about an effective approach to apply PLE in secure environments and in conjunction with System Security Engineering.




29th Annual INCOSE international symposium
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July 20 - 25, 2019

Applying Feature-Based Systems and Software Product Line Engineering in Unclassified and Classified Environments

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9 by Jim Teaff, Bobbi Young, and Paul Clements. Permission granted to INCOSE to publish and use.

erospace and defense companies are reaping the benefits of feature-based re product line engineering and management (FBPLE) in those situations ust seamlessly span unclassified and classified environments (Gregg et al. 2015) (Krueger et al. 2014) (Lanman et al. 2011). These benefits include talent while awaiting access to classified material; leveraging employees who er sovereign states; and optimizing system production and maintenance for his whitepaper we present the architectural design and accompanying business factory and its artifacts that comprise unclassified and classified digital as- assets are used in automated generation of unclassified and classified product uction activities occur within a single logical enterprise spanning multiple comprising multiple security zones[2].

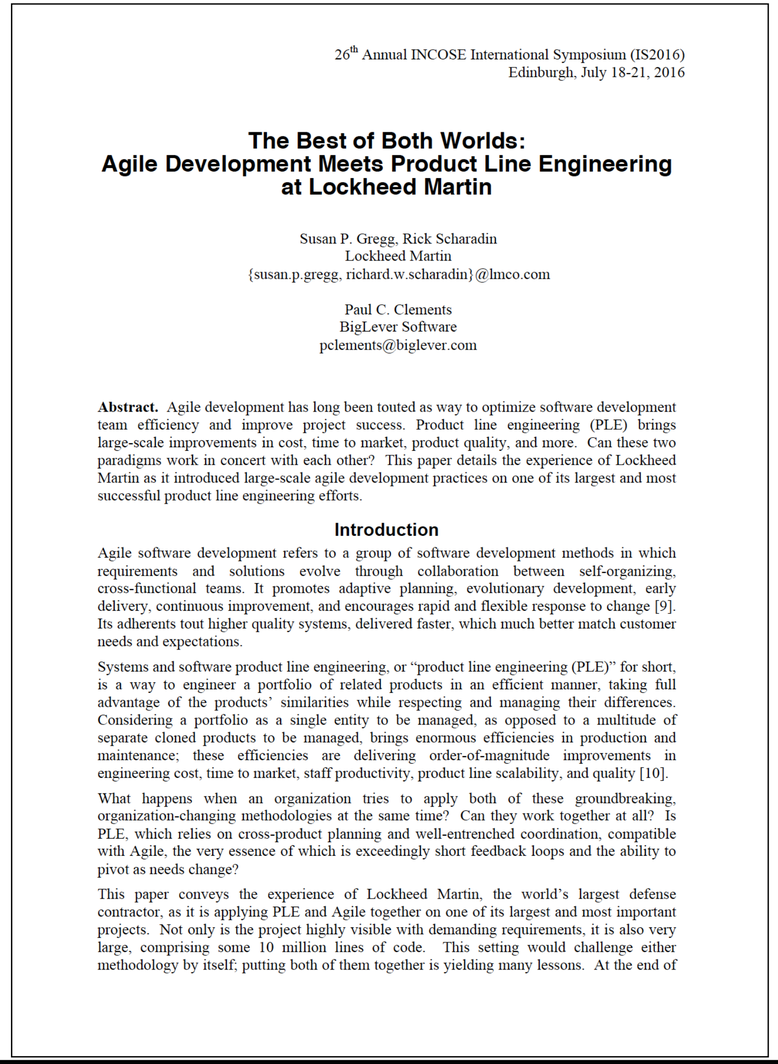
acts that can be managed on an information system, and include software, hardware design aterials, team schedules & other management artifacts, and more.

context is a collection of one or more information system segments with rules-driven control traffic, establishing a perimeter within which sensitive or classified information is processed.

n technology or Technical Data controlled under either the U.S. International Traffic in Arms Regulations or the U.S. tions.

Feature-based PLE and Agile

- As DoD follows industry trends in Agile development, can Feature-based PLE play effectively in these arenas?
- PLE is not applied in isolation.
- Raytheon, Lockheed Martin, General Dynamics, and (for good measure) General Motors have all shared their experience, which amounts to a resounding “yes.”



26th Annual INCOSE International Symposium (IS2016)
Edinburgh, July 18-21, 2016

The Best of Both Worlds:
Agile Development Meets Product Line Engineering at Lockheed Martin

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Abstract. Agile development has long been touted as way to optimize software development team efficiency and improve project success. Product line engineering (PLE) brings large-scale improvements in cost, time to market, product quality, and more. Can these two paradigms work in concert with each other? This paper details the experience of Lockheed Martin as it introduced large-scale agile development practices on one of its largest and most successful product line engineering efforts.

Introduction

Agile software development refers to a group of software development methods in which requirements and solutions evolve through collaboration between self-organizing, cross-functional teams. It promotes adaptive planning, evolutionary development, early delivery, continuous improvement, and encourages rapid and flexible response to change [9]. Its adherents tout higher quality systems, delivered faster, which much better match customer needs and expectations.

Systems and software product line engineering, or “product line engineering (PLE)” for short, is a way to engineer a portfolio of related products in an efficient manner, taking full advantage of the products’ similarities while respecting and managing their differences. Considering a portfolio as a single entity to be managed, as opposed to a multitude of separate cloned products to be managed, brings enormous efficiencies in production and maintenance; these efficiencies are delivering order-of-magnitude improvements in engineering cost, time to market, staff productivity, product line scalability, and quality [10].

What happens when an organization tries to apply both of these groundbreaking, organization-changing methodologies at the same time? Can they work together at all? Is PLE, which relies on cross-product planning and well-entrenched coordination, compatible with Agile, the very essence of which is exceedingly short feedback loops and the ability to pivot as needs change?

This paper conveys the experience of Lockheed Martin, the world’s largest defense contractor, as it is applying PLE and Agile together on one of its largest and most important projects. Not only is the project highly visible with demanding requirements, it is also very large, comprising some 10 million lines of code. This setting would challenge either methodology by itself; putting both of them together is yielding many lessons. At the end of

Feature-based PLE and Digital Engineering / Model-Based Engineering

- As DoD leads industry trends by mandating advanced digital engineering and model-based approaches, Feature-based PLE becomes critical.
  - "Nobody builds just one"
  - Early generation product line engineering approaches are intractable for digital engineering
- Raytheon, Lockheed Martin, General Dynamics, and (for good measure) General Motors have all shared their experiences.

Product Line Engineering Meets Model Based Engineering in the Defense and Automotive Industries

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ABSTRACT

Product line engineering and model based engineering are two powerful engineering approaches that each bring significant advantages to system engineering projects. This paper explores how three companies – Raytheon, General Dynamics, and General Motors – are combining these two paradigms in unique and innovative ways in very challenging application domains to achieve engineering goals of critical importance to them.

CCS CONCEPTS

• Software and its engineering → Software product lines;

KEYWORDS

Product line engineering, model-based engineering, feature models, feature profiles, variation points, product configurator, feature-based product line engineering, PLE factory.

ACM Reference Format: Bobbi Young, Rick Flores, Judd Cheatwood, Todd Peterson, Paul Clements, Product Line Engineering Meets Model Based Engineering in the Defense and Automotive Industries. *In Proceedings of SPLC '17*, Sevilla, Spain, September 25-29, 2017, 10 pages.

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1. INTRODUCTION

Model based engineering is "an approach to engineering that uses models as an integral part of the technical baseline that includes the requirements, analysis, design, implementation, and verification of a capability, system, and/or product throughout the acquisition life cycle" [6]. A model, in turn, is "a physical, mathematical, or otherwise logical representation of a system, unity, phenomenon, or process" [2]. Model based engineering is held in contrast to approaches in which informal prose or diagrams serve as the basis for the information exchange among stakeholders in a systems engineering process. Models, because of

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2. FEATURE-BA
ENGINEERING

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Figure 1 PLE as a fa
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In Feature-based PLE, th
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Unrestricted Content

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How Missile Engineering is Taking Product Line Engineering to the Extreme at Raytheon

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ach to designing and building missiles by Raytheon
f the approach include (1) modular common compo-
, (2) modular open systems approaches and standards
Line Engineering (FbPLE) practices for identifying
) implementing digital transformation through digital
digital twin. Much more ambitious than simply reus-
asly built missiles, this approach involves automatic
tomatically generated trade space of *possible* missile
nts. The goal is to radically lower development and
le design that can be taken to design validation, then
l ecosystem. The paper focuses on the FbPLE aspect
its technology is used to create and manage the trade
sen design.

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Model Based Engineering and Product Line Engineering: Combining Two Powerful Approaches at Raytheon

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Abstract. Model based engineering (MBE) refers to a systems engineering approach that employs models as an integral part of a system's engineering stream, providing a formality and semantic rigor that lends itself to analysis and prediction, thus enabling earlier detection of problems. Product line engineering (PLE) is a way to engineer a portfolio of related products in an efficient manner, taking full advantage of the products' similarities while respecting and managing their differences. Raytheon, one of the world's largest defense contractors, is applying PLE and MBE together and combining the benefits of each. This paper will show how Raytheon is using the two methodologies to support each other, and the lessons it is learning as it does so.

Introduction

Model based engineering (MBE) refers to a systems engineering approach that employs *models* as an integral part of a system's engineering stream. Models typically bridge the gap between engineering activities, and provide a formality and semantic rigor that lends itself to analysis and prediction, thus enabling earlier detection of problems. The formality can also lend itself to automation that can transform a model into another formal representation of the system, typically, one that is "closer" to the final implementation or realization. This automation can reduce the time, effort, and errors that are associated with the manual translation that would otherwise be required.

Systems and software product line engineering, or "product line engineering (PLE)" for short, is a way to engineer a portfolio of related products in an efficient manner, taking full advantage of the products' similarities while respecting and managing their differences. Considering a portfolio as a single entity to be managed, as opposed to a multitude of separate cloned products to be managed, brings enormous efficiencies in production and maintenance; these efficiencies are delivering order-of-magnitude improvements in engineering cost, time to market, staff productivity, product line scalability, and quality [10].

What happens when an organization tries to apply both of these groundbreaking, organization- changing methodologies at the same time? Can they work together at all? This paper conveys the experience of Raytheon, one of the world's largest defense contractors, as it is seeking to apply PLE and MBE together.

What Is Product Line Engineering?

Product line engineering (PLE) is a way to engineer a portfolio of related products in an efficient manner, taking full advantage of the products' similarities while respecting and

Feature-based PLE in a V&V-intensive environment

- Few sectors come close to A&D in terms of the cost required to validate systems.
- Aerospace companies have reported up to 8-fold improvements in the time to generate a certification package, cutting the time from weeks to days.
- Lockheed Martin reports that V&V can in many cases be shared among multiple members of a product line, saving significant time and money.

Product Line Engineering on the Right Side of the "V"

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ABSTRACT

Product line engineering (PLE) is well-known for the savings it brings to organizations. This paper shows how a very large, in-service systems and software product line is achieving PLE-based savings in their verification and validation phase of development. The paper addresses how to achieve the sharing across product variants while the products being tested are evolving over time. Additionally, we will give a pragmatic set of decision criteria to help answer the longstanding issue in PLE-based testing of whether to test on the domain side or the application (product) side of the product derivation process.

CCS CONCEPTS

• **Software and its engineering → Software product lines;**

KEYWORDS

Product line engineering, software product lines, feature modeling, feature profiles, bill-of-features, variation points, product portfolio, product configurator, second generation product line engineering, PLE factory, AEGIS Combat System

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1 INTRODUCTION

This paper tells the story of how a very large systems and software product line is harvesting the benefits of product line engineering on the right-hand side of the engineering "V" model – that is, in the verification and validation activities associated with product deployment.

Product line engineering (PLE) is well-known for the game-changing savings it brings to organizations (for example, [5][14][19][25][22][23]), compared to one-at-a-time development or worse, parallel development. Case studies have, in the past, most often focused on the development activities involved in the *creation* of system artifacts – activities on the left side of the "V". PLE literature certainly acknowledges and touts the potential savings available from the testing side, but case studies focusing on how to gain those benefits in practice are not as plentiful.

This paper shows how a very large, industrial-strength, in-service systems and software product line is achieving PLE-based V&V savings. The product line that is the subject of this paper is the AEGIS Weapons System, a large and complex naval command and control system in wide use in several navies around the world; the developing organization is Lockheed Martin, the world's largest defense contractor, employing 125,000 people worldwide.

The paper confirms that significant savings can be achieved from sharing V&V activities and artifacts across product variants in a product line, but the story of how it does so takes an unexpected twist. How do you manage that sharing when the products you are testing are continuously evolving in response to updated requirements and the need for additional variants? We will show how technical management policies drive V&V-based savings.

Finally, a longstanding issue in PLE-based testing is whether to test on the domain side or the application (product) side of the product derivation process. We will show how Lockheed Martin answers that question pragmatically for AEGIS.

2 AEGIS

The product line being described here is the AEGIS Weapons System, which is the major command-and-control component of the AEGIS Combat System. AEGIS is a highly integrated naval ship combat system in service on over 100 ships in the U.S. Navy and elsewhere. AEGIS cruisers and destroyers constitute the majority of the U.S. surface Navy and will continue to form the core of the U.S. surface fleet for the next several decades. The AEGIS Combat System is capable of simultaneous warfare on many fronts: anti-air, anti-surface, anti-submarine, and strike warfare. AEGIS, or a carefully chosen functional subset, is deployed on some 100 naval vessels in the U.S. Navy, navies of several key U.S. allies across the globe, vessels of the U.S. Coast Guard, and even land-based ballistic missile defense installations. AEGIS is a system that protects assets from airborne attack from aircraft or missiles. It detects airborne threats, plans how to engage them, and launches missiles to intercept and neutralize them (Figure 1).

The mission of AEGIS includes

- self-defense (protecting the host platform from attack)
- area air defense (for example, protecting a naval task force that includes the host platform)
- long-range air defense and ballistic missile defense (for example, protecting a geographical area from long-

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Summary

- The release of ISO/IEC 26580 is good news for the systems engineering community in general, and A&D in particular
  - Can be readily and unambiguously mandated in RFPs and contracts
  - Can be readily and unambiguously applied by contractors in their proposals and deliverables
- The better news is that Feature-based PLE does not need a break-in period for A&D to learn the ropes
  - It’s been here all along, and continues to be ready to serve

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