Challenges and Opportunities in Aeronautical Design, Engineering and Manufacturing

Earll M. Murman

MIT

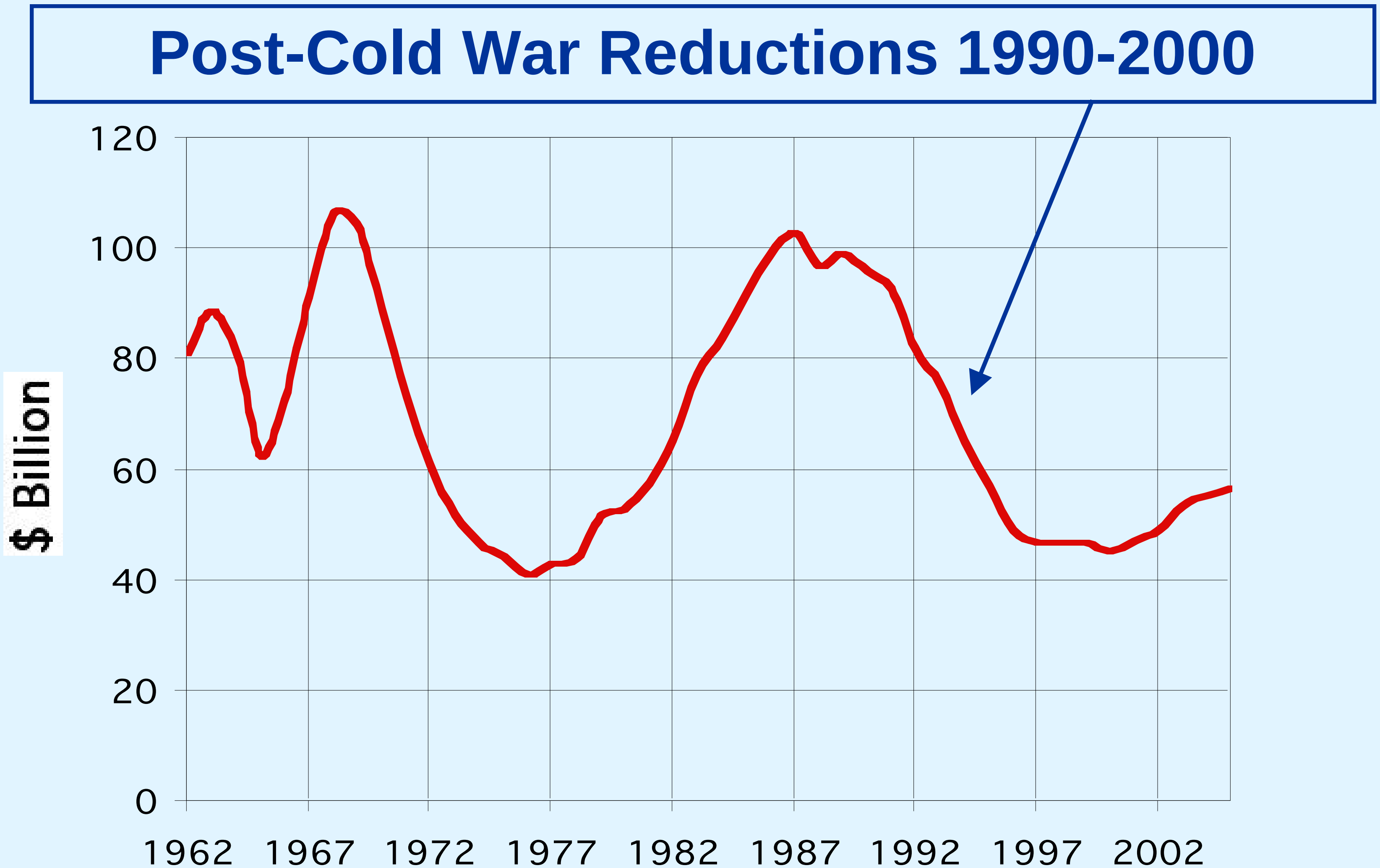
May 1, 2001

Outline

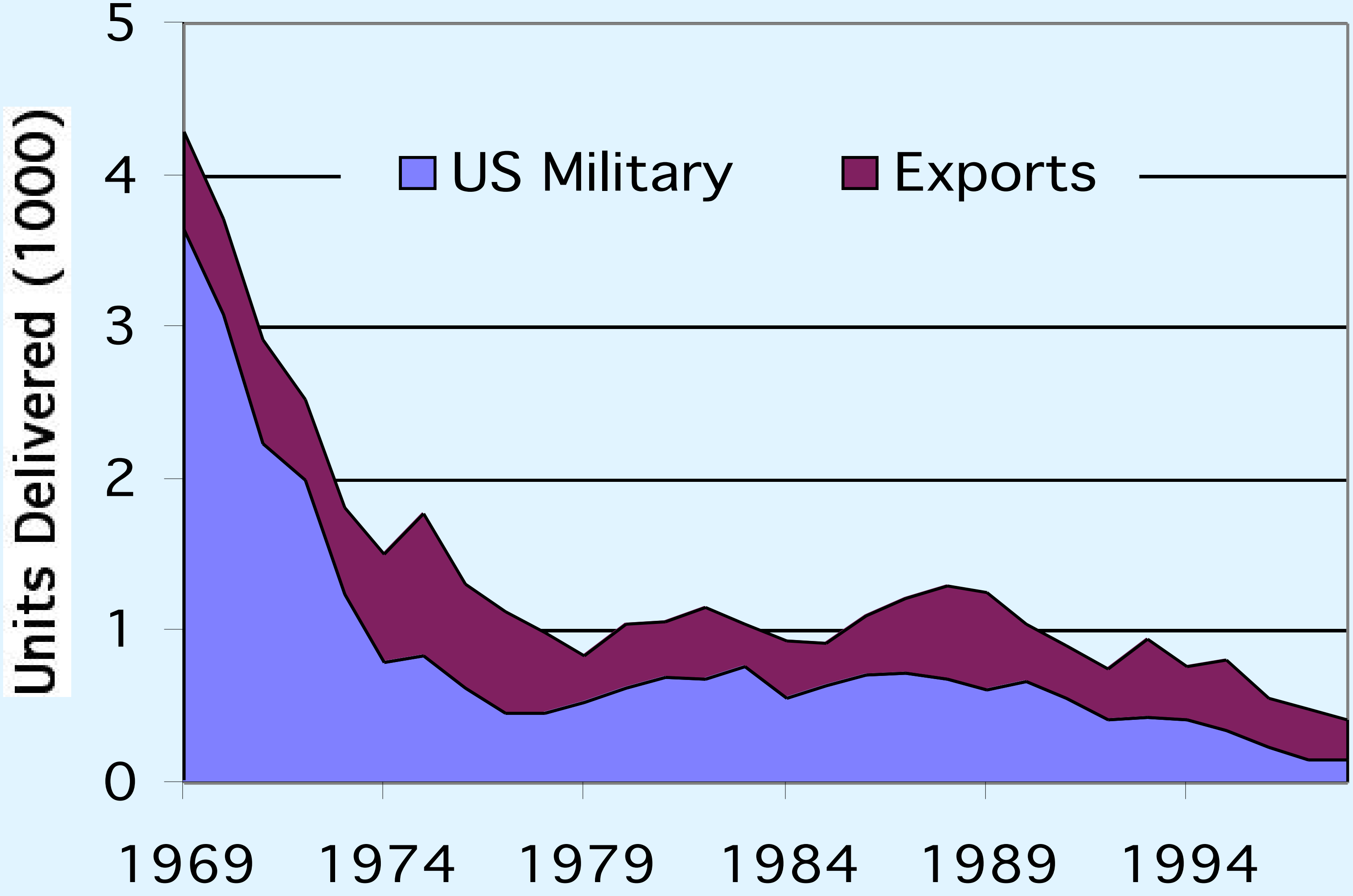
- Post-Cold War landscape
- Dynamics of Industrial Innovation
- “Lean”
- “Value”
- Challenges and Opportunities for Aeronautical Design, Engineering Manufacturing

DoD Modernization Budget

Constant 1996 Dollars

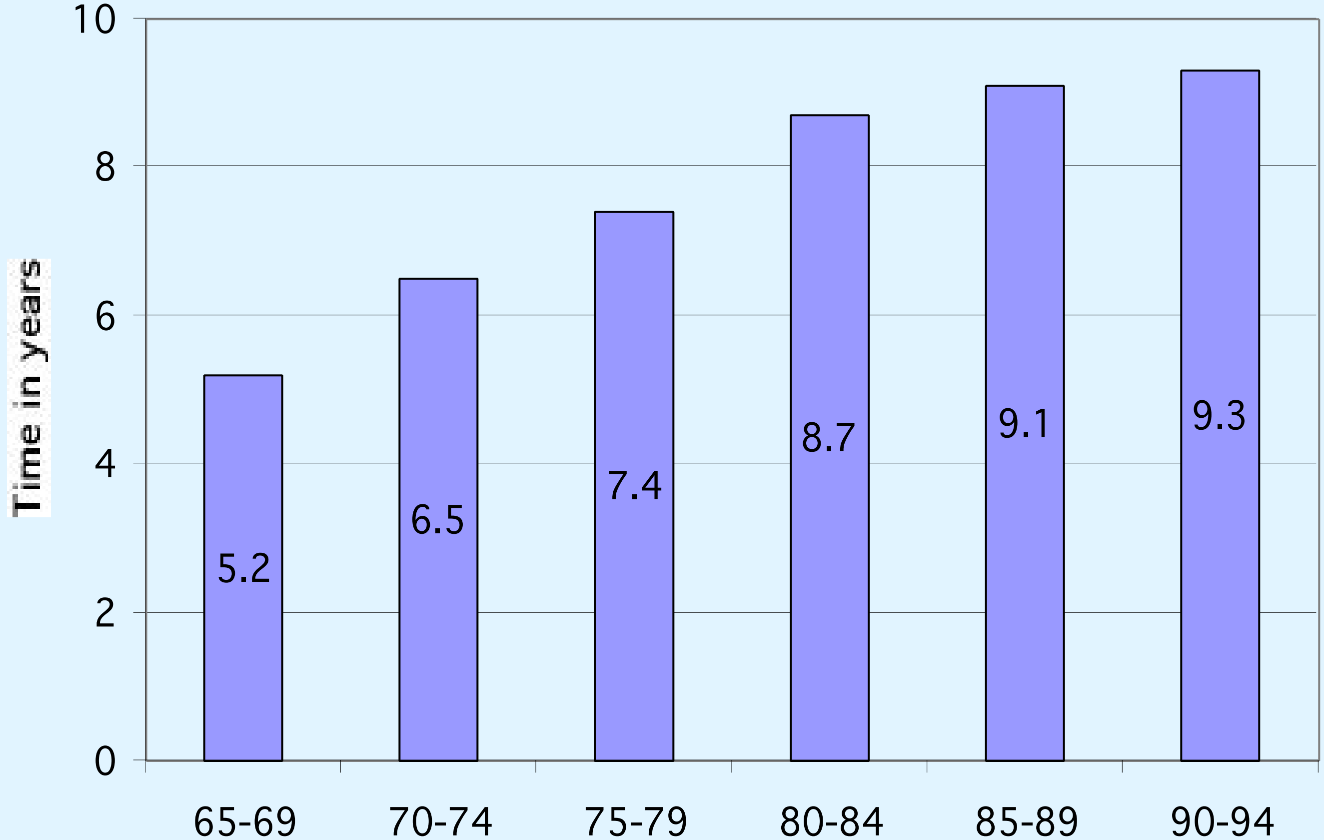


US Military Aircraft Deliveries



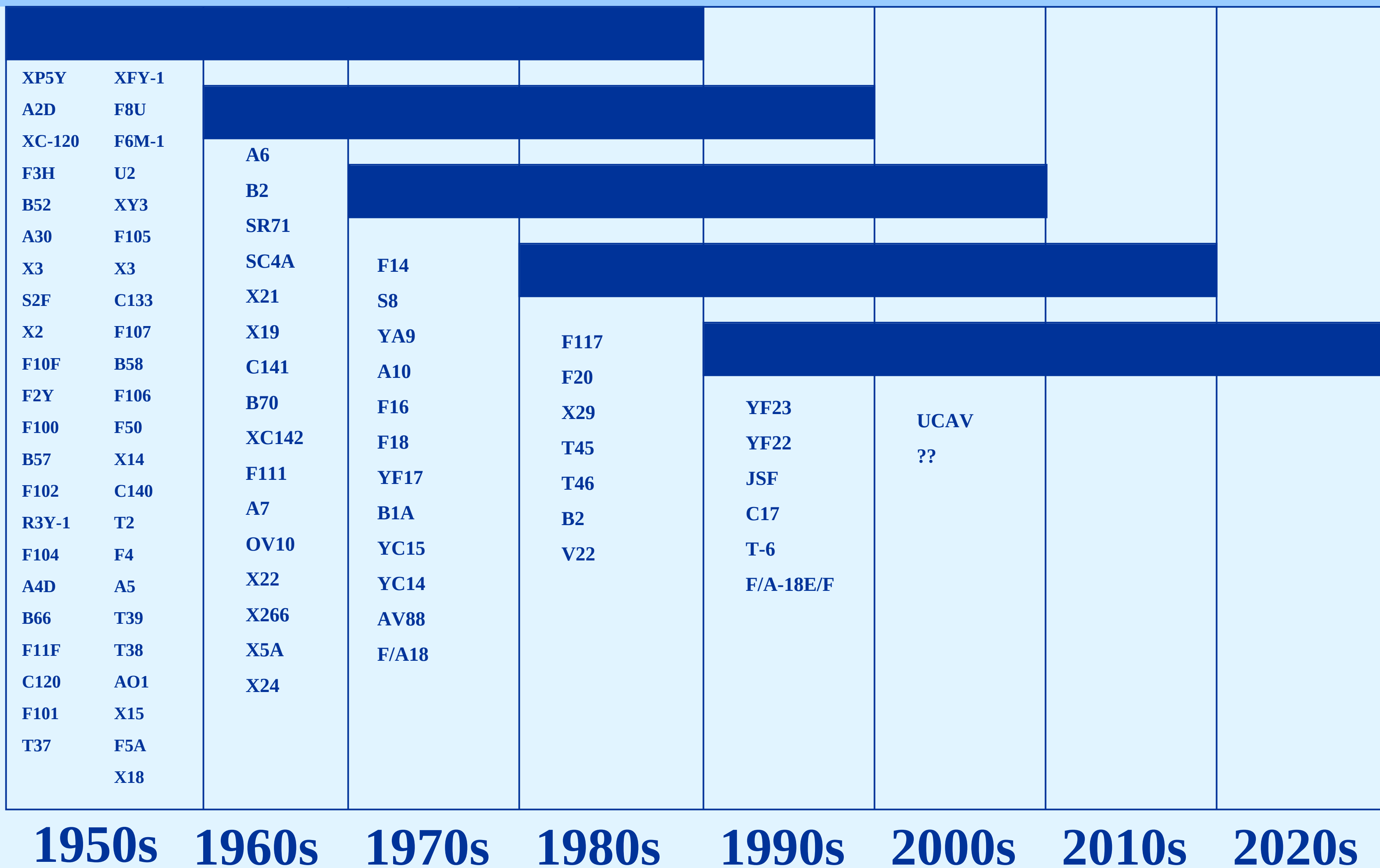
Fewer aircraft - greater percentage exported

Development Time for Major US DOD Systems



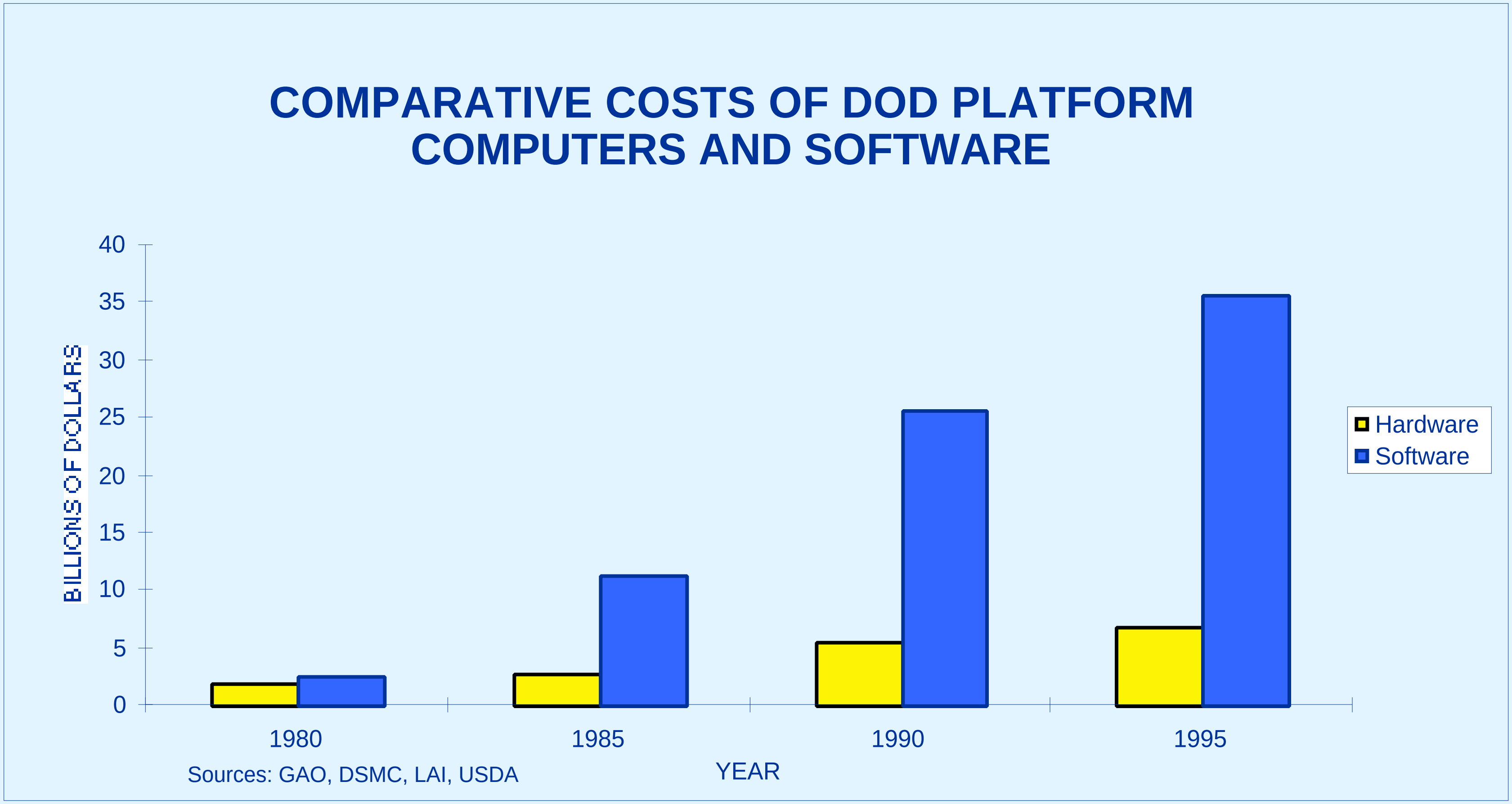
Possible causes: System complexity; Inefficiencies in acquisition, design, development, manufacturing

Engineer Career Length vs New DoD Designs
Fewer New Designs, More Derivatives



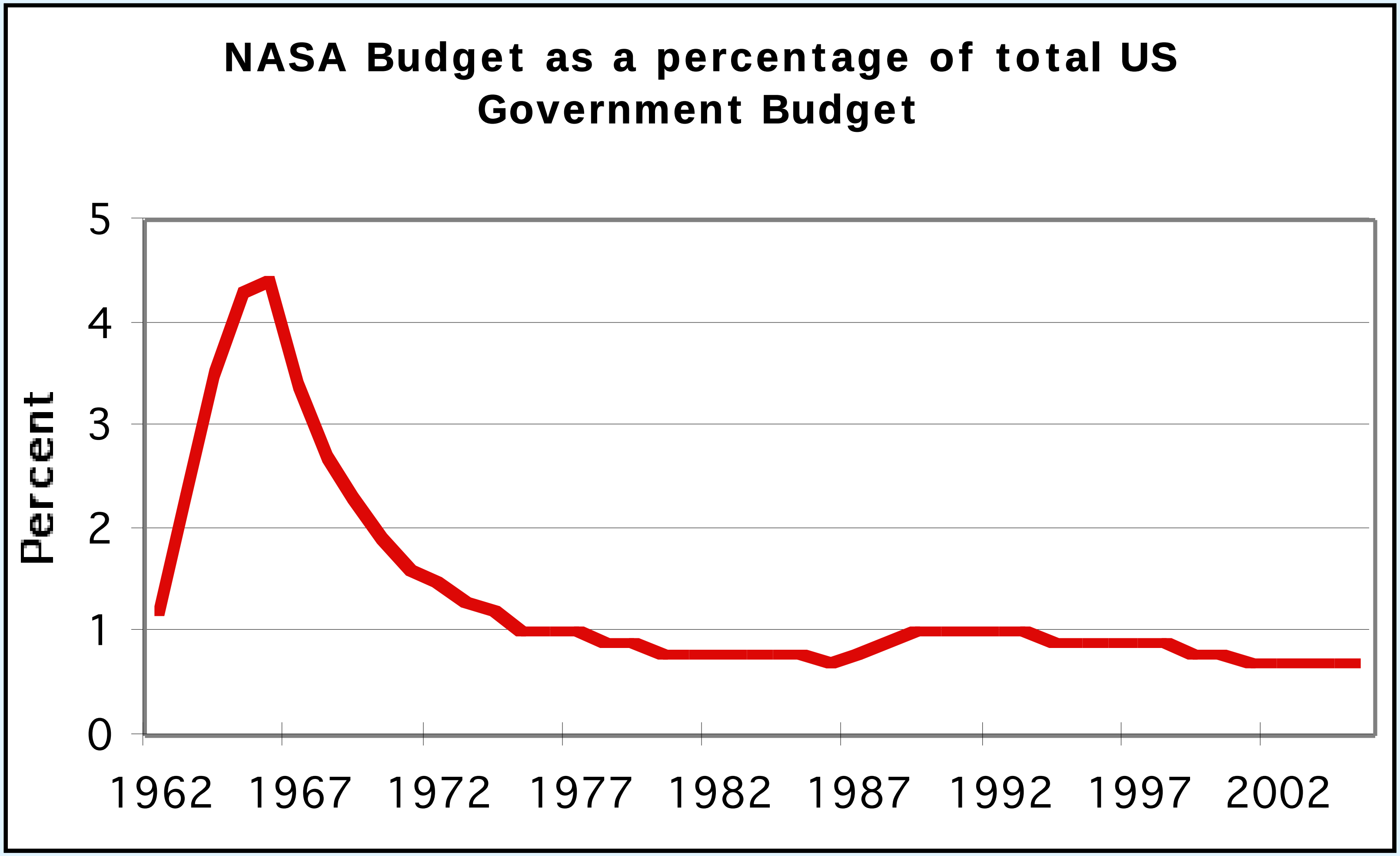
Source: Hernandez, C. Intellectual Capital White Paper for The California Engineering Foundation, 12/07/99

Hardware vs. Software Costs
All DoD Embedded Systems



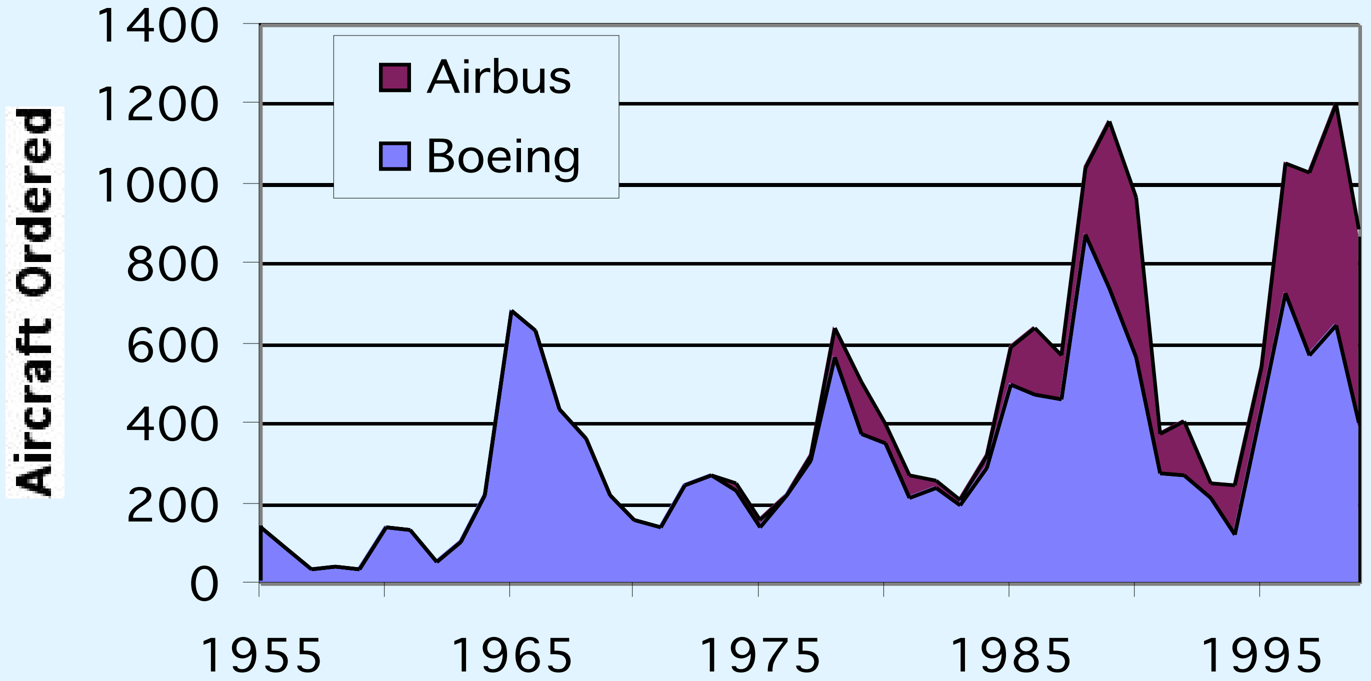
Exponentially growing software costs!

NASA Budget



Public support NASA is < 1% of Federal Budget

Commercial Transports

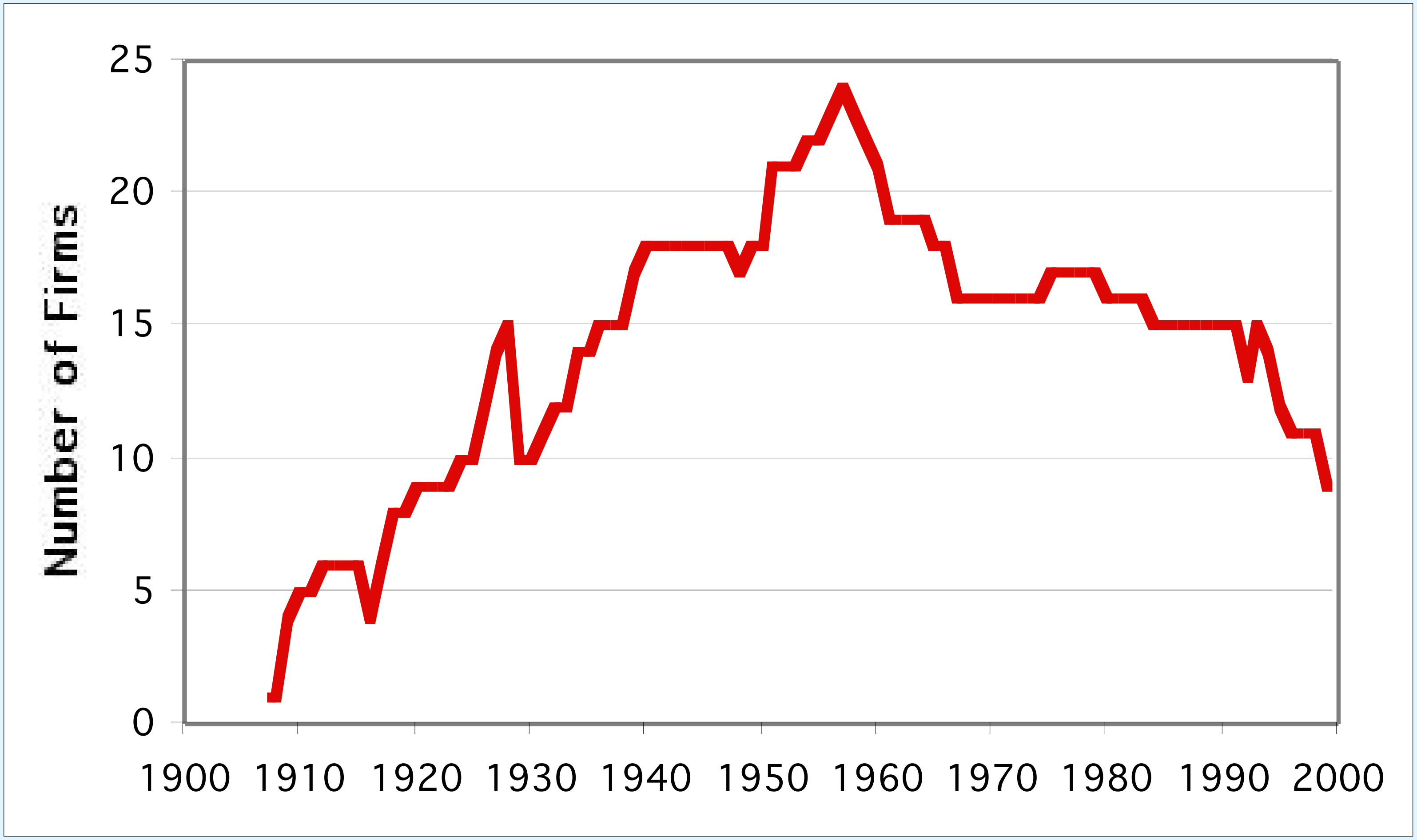


- **Declines in the early 90s**
- **Emergence of duopoly**
- **Discriminators: price, DOC, time-to market, aircraft family**

Post-Cold War Landscape

- ✈ Reduced budgets
- ✈ Increased DoD development times
- ✈ Increasing costs, e.g. software
- ✈ Legacy military aircraft from Cold War
- ✈ More foreign competition
- ✈ Cold War "Monuments"
  - National and Global
  - Institutions & infrastructure
  - Education
  - Mental

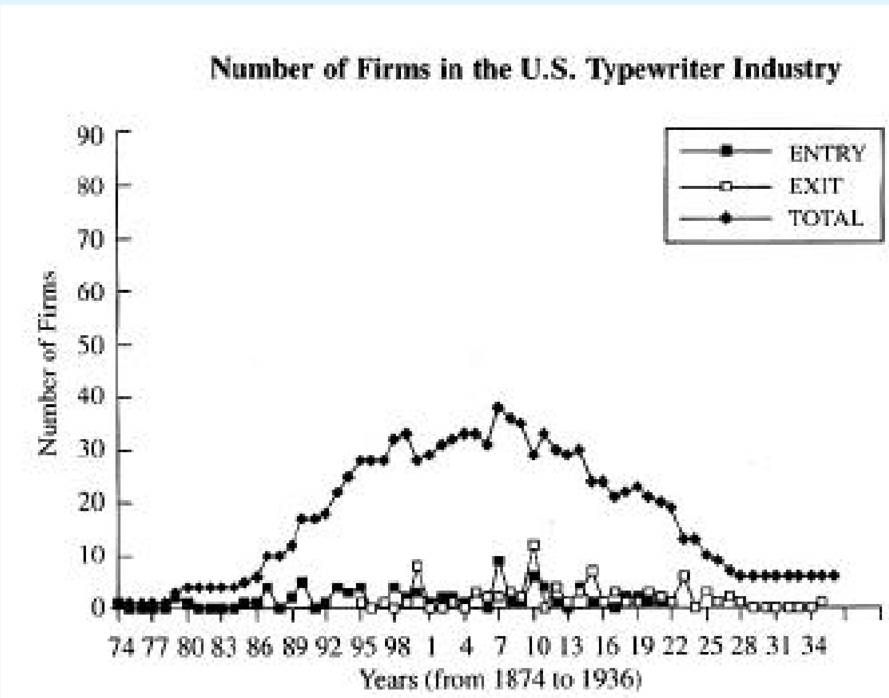
Major US Aerospace Firms vs Years

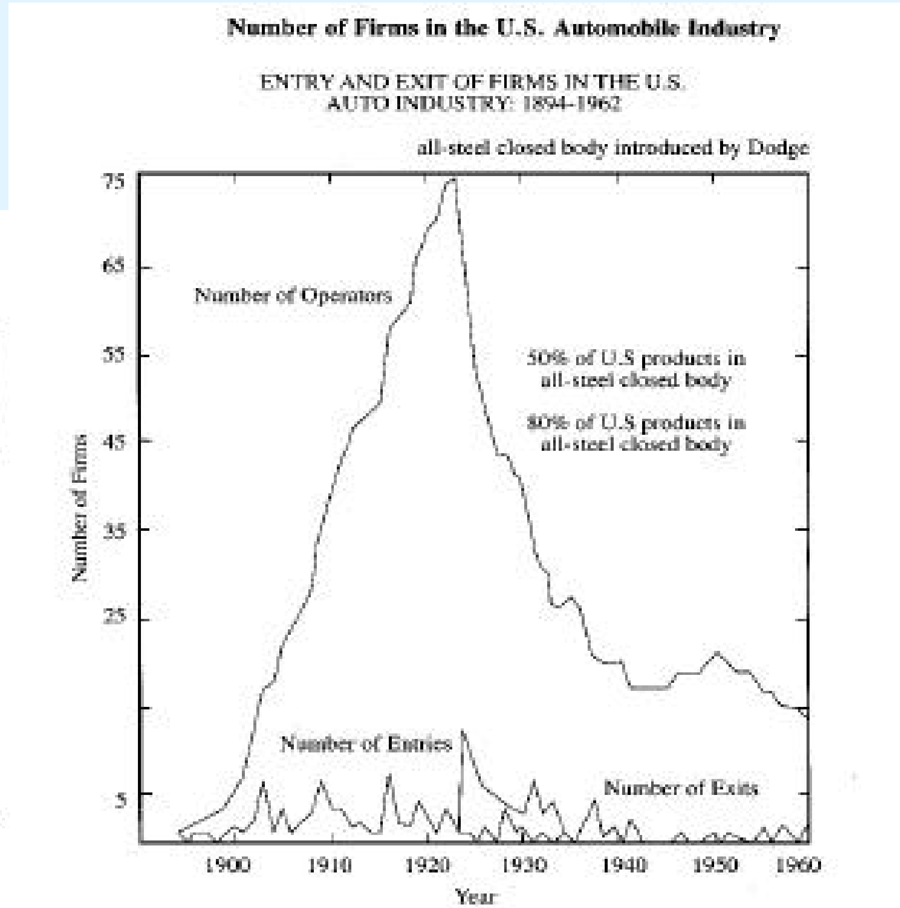


Industrial evolution studied by Utterback

Source: Weiss, S. and Amir, A, The Aerospace Industry, Encyclopedia Britannica, 1999

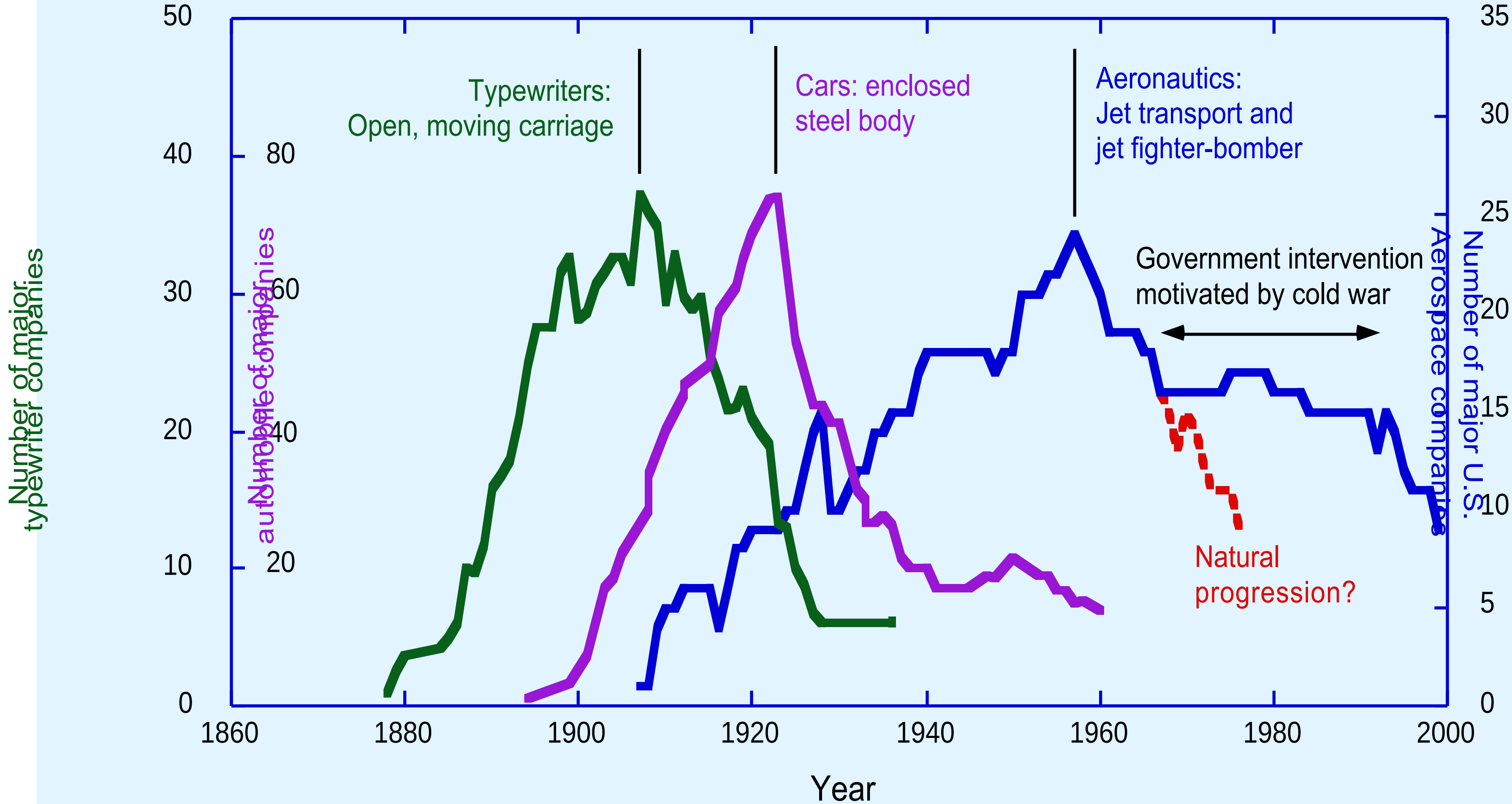
Evolution in Other Industries





Typewriters **Automobiles**

Emergence of a Dominant Design

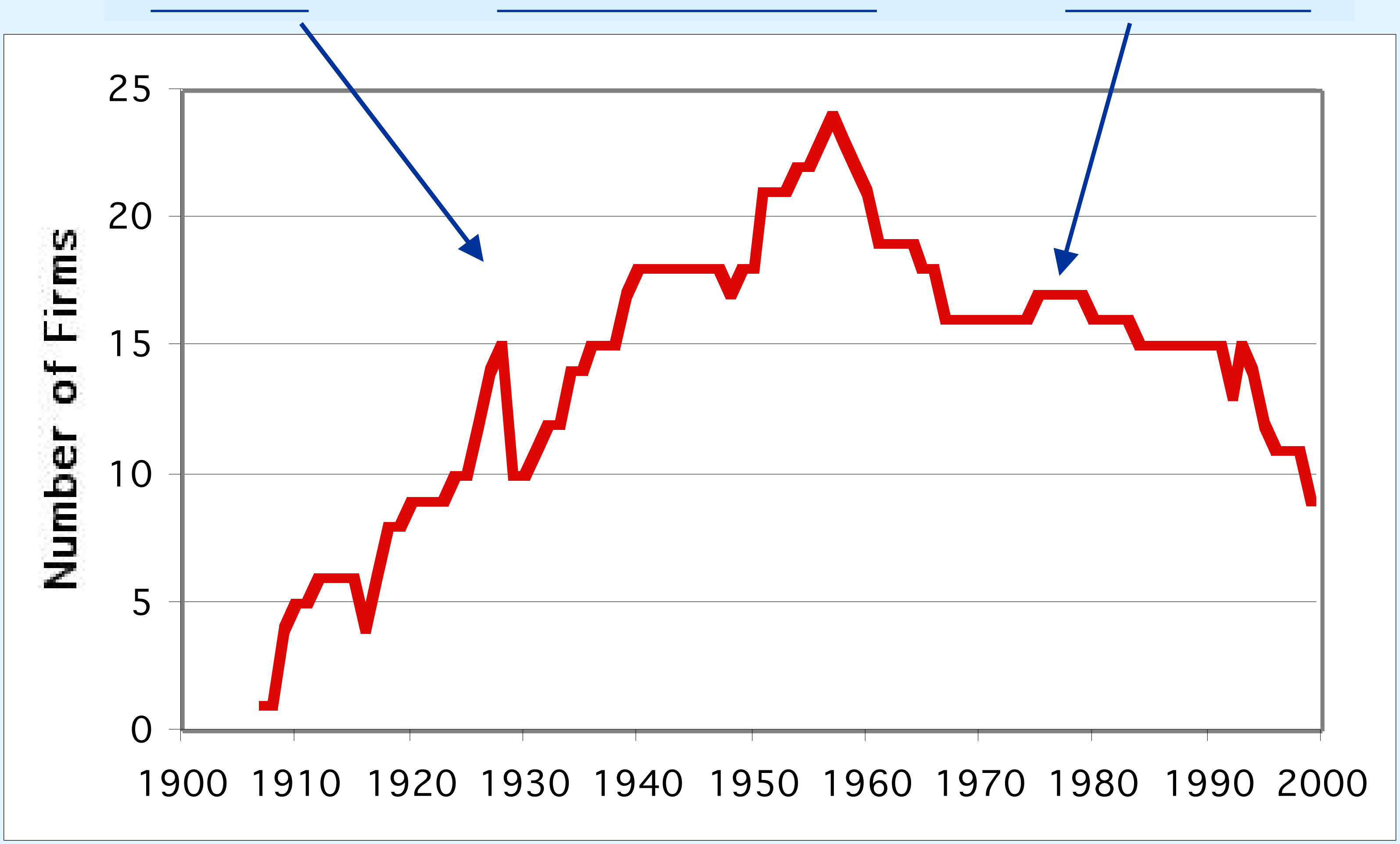


Factors Contributing to Evolution of Dominant Design

- Technology
- Timing
- Infrastructure
- Individual entrepreneurs
- Customer expectations
- ……

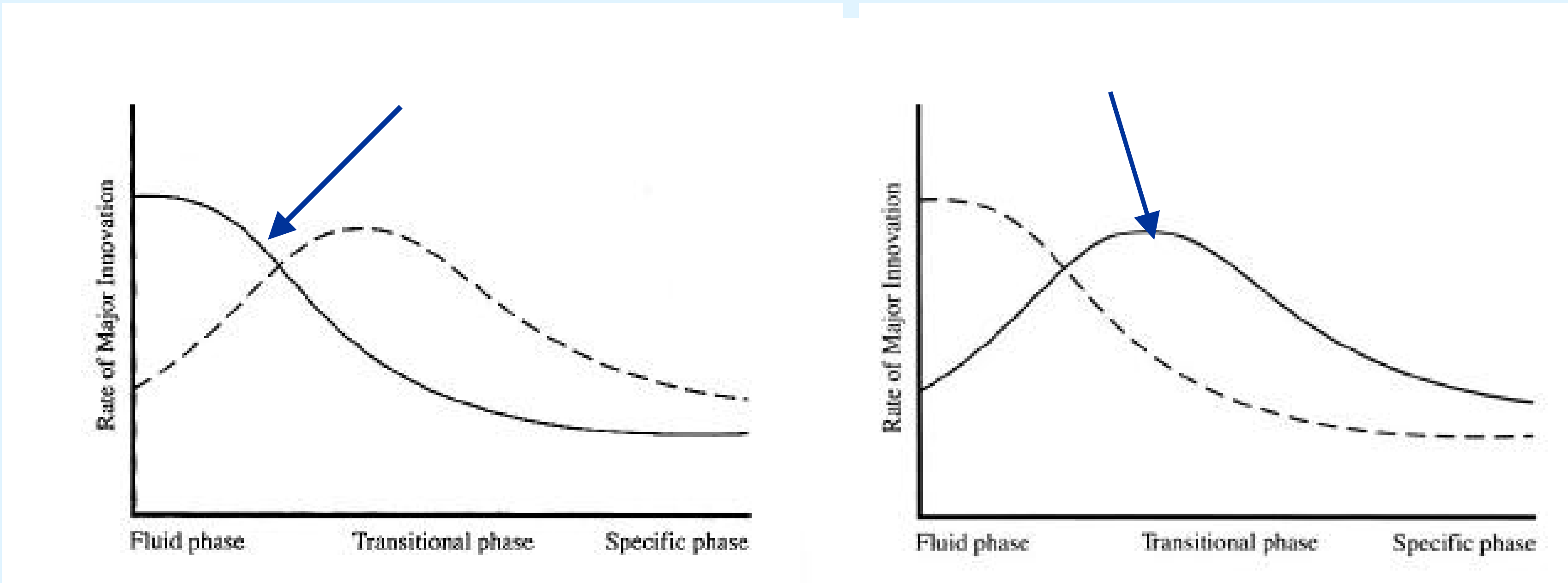
More than just advanced technology

Phases of Industrial Evolution



Specific* is better terminology than *Mature

Utterback's Theory



- Product Innovation dominates fluid phase
- Process innovation dominates later phases
- Aircraft are well into the specific phase - dominant designs have emerged

Characteristics of the Specific Phase

Attribute	Characteristics
Innovation	Incremental for product and with cumulative improvements in productivity and quality.
Source of Innovation	Often suppliers
Products	Mostly undifferentiated, standard products
Production processes	Efficient, capital intensive, and rigid; cost of change high
R & D	Focus on incremental product technologies; emphasis on process technology
Equipment	Special-purpose, mostly automatic, with labor focused on tending and monitoring equipment
Plant	Large-scale, highly specific to particular products
Cost of process change	High
Competitors	Few; classic oligopoly with stable market shares
Basis of competition	Price
Organizational control	Structure, rules, goods
Vulnerabilities of industry leaders	To technological innovations that present superior product substitutes.

Product Innovation Opportunities in the Specific Phase

"Incremental in product technologies with cumulative improvement in productivity and quality", e.g.

- Increased range-payload
- Reduced noise, emissions
- Improved safety
- Improved passenger satisfaction
- Improved reliability

Numerous opportunities

Process Innovation Opportunities in the Specific Phase

"R&D Emphasis on process technology", e.g.

- Improved design methods
- Improved development methods
- Improved manufacturing methods

R & D investments in process technology have grown in importance in the 1990s following neglect during the Cold War.

Superior Product Substitutes

- Leaders are vulnerable to "Technological innovation that present superior product *substitutes*"
  - Will there be a superior product to displace aircraft?
  - Will electronic communication reduce air travel?
  - Personally I don't think so!

Aviation is central to national security and the global movement of people and goods in the New Economy.

Superior Product Substitutes - Will There Be New Configurations?

- **Recent candidates**
  - **High Speed Civil Transport**
  - **Supersonic Business Jet**
  - **Sonic Cruiser**
  - **Blended Wing Body**
  - **Uninhabited Combat Air Vehicle**
  - **Deformable aircraft**

Superior *Value* required to *displace* dominant design - a tall order!!

More Likely Innovation Opportunities in the Specific Phase

- Exploit the dominant design
- Consider opportunities at the system level, not the product level
- Expand markets and attract new customers - displace other products, not our own.
- Exploit new technologies for superior subsystem capability

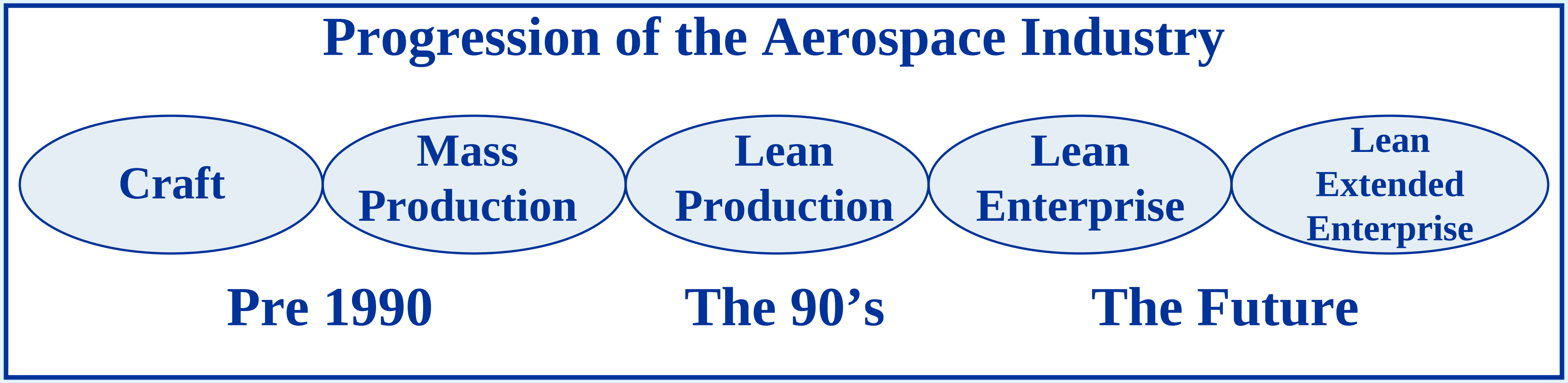
Candidates for Innovation

- "Hassle-free" travel (Womack and Fitzpatrick)
  - End-to-end, weather insensitive travel
  - Passenger comfort, convenience
- Short haul from local airports
  - Civilian low noise "stealth" aircraft
  - Reduced crew demands to lower DOC
- Fully integrated air and space service to the war fighter
- Sensor and information subsystems

Role of Manufacturing

- Utterback's studies span the era of mass production
  - Focus on economies of scale
  - Large capital investment in equipment
  - Humans as specialists
  - Under valuation of labor as source of innovation
- Will the new production paradigms in the knowledge driven economy change the dynamics of innovation?

Lean



- Lean is a new industrial paradigm
- Lean emerged from the Japanese auto industry
- Lean is focused on delivering value and responding to opportunities with minimum use of resources

Lean and Aerospace

- Aerospace industry & government agencies started their "journey to Lean" in the early 90s
- Research consortiums initiated
  - US - The Lean Aerospace Initiative (LAI) at MIT (1993)
  - UK - The UK LAI at Warwick, Bath, Cranfield, Nottingham (1997)
  - Sweden - The Lean Aircraft Research Program at Linköping (1997)

The US LAI Community

Industry, Government, Labor, Academic Partnership

Avionics/Missiles

BAE Systems North America
Hewlett Packard
Northrop Grumman ESSS
Raytheon Systems Co.
Raytheon Systems and Electronics Sector
Rockwell Collins, Inc.
Textron Systems Division

Space

Boeing Space & Communications
GenCorp Aerojet
Lockheed Martin Space & Strategic Missiles
Northrop Grumman ESSS Space Sector
Spectrum Astro
TRW Space and Electronics

Airframe

Boeing Military Aircraft & Missiles
Boeing Commercial Airplane Group
Boeing Phantom Works
Lockheed Martin Aeronautical Systems
Northrop Grumman ISS
Raytheon Aircraft Co.
Sikorsky

MIT

School of Engineering
Aerospace
Mechanical
Sloan School of Management
Center for Technology, Policy,
and Industrial Development

Other Participants

UAW
IAM
AIA
DSMC
IDA
International Collaborations:
Linköping University
Warwick, Bath, Cranfield
Nottingham Universities

Propulsion/Systems

Curtis Wright Flight Systems
Parker Aerospace
Hamilton Sundstrand
Pratt & Whitney
Rolls Royce (N.A.)

US Air Force

Aeronautical Systems Center
Air Force Research Laboratory
(Materials and Manufacturing Directorate)
Space and Missile Center
SPOS: JSF, F-22, C-17, Training (JPATS)

Other Government

DCMA
NASA
NAVAIR
AMCOM
OUSD(A&T)
NRO

Lean Enterprise Model

Architecture and Overarching Practices

Meta-Principles/Enterprise Principles

Enterprise Level Metrics

Overarching Practices

- Identify & Optimize Enterprise Flow
- Assure Seamless Information Flow
- Optimize Capability & Utilization of People
- Make Decisions at Lowest Possible Level
- Implement Integrated Product & Process Development
- Develop Relationships Based on Mutual Trust & Commitment
- Continuously Focus on The Customer
- Promote Lean Leadership at all levels
- Maintain Challenge of Existing Processes
- Nurture a Learning Environment
- Ensure Process Capability and Maturation
- Maximize Stability in a Changing Environment

Metrics - Barriers - Interactions

Data Sheets (~225)

Enabling Practices (~ 60)
Metrics - Data - Barriers - Interactions

Supporting Practices (~ 300)

Internet Links (~600)

Examples of Lean Results

- Release engineering
- Forward fuselage design/production
- Precision assembly
- C-17 cost reduction, quality improvement, delivery schedule
- Northrop Grumman throughput time
- F/A-18E/F: *An Evolving Lean Enterprise*

Goal: Reduce product cycle time and cost while increasing quality and performance

Lean Practices Applied to Release Engineering

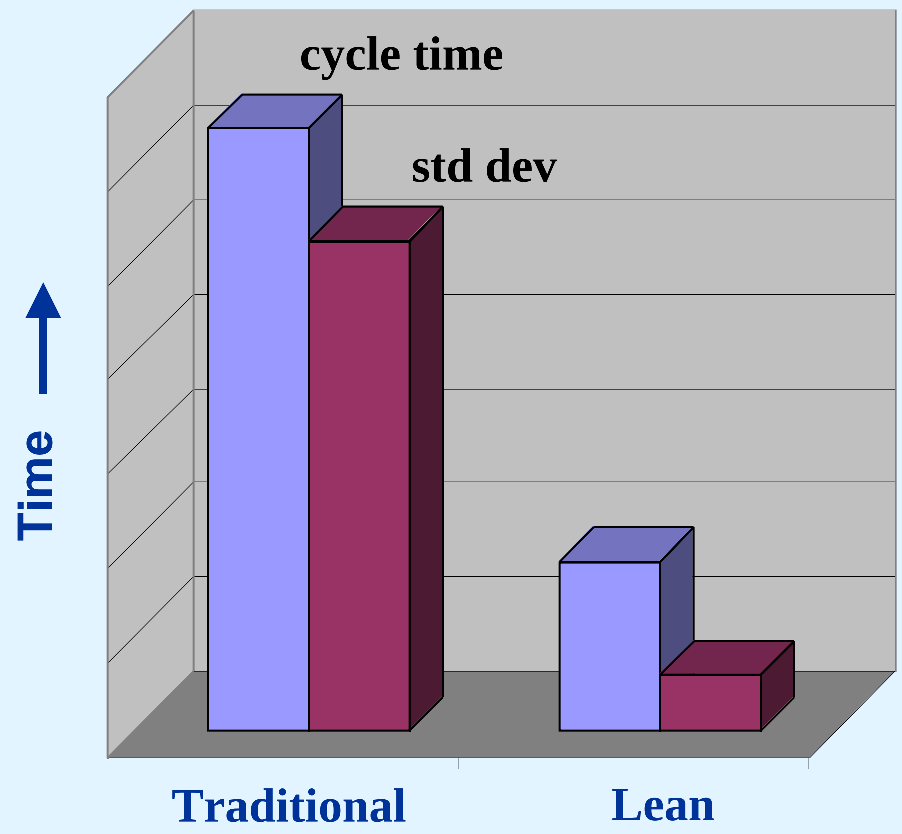
Lockheed Martin
Aeronautics Company-Marietta

- •Reduced Cycle time by 73%
- •Reduced Rework of Released Engineering from 66% to <3%
- •Reduced Number of Signatures 63%

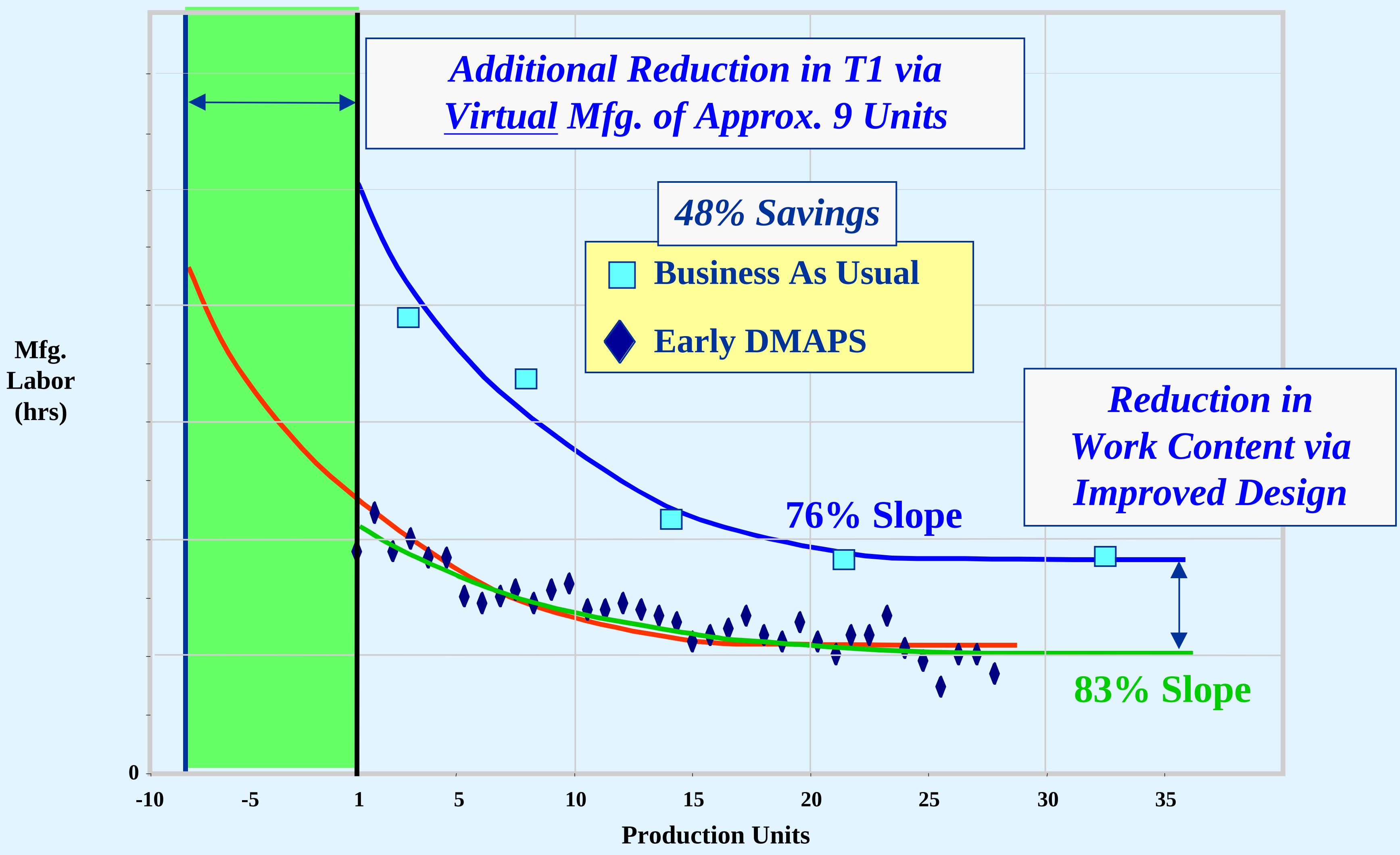
Typical Result: Tracing Change

Cycle time reduced *and* lower std. dev.

More predictable process



Application of Lean Practices to Forward Fuselage - Boeing Military A/C



Precision Assembly

Old Paradigm
Tooling defines part location

New Paradigm
Parts themselves define location

- Drive to 6 sigma processes
- Precision assembly
  - Parts define location
  - Reduced assembly tooling
  - Remove trim and shim from assembly

Process understanding key to precision improvement

Toolless Assembly Case Study

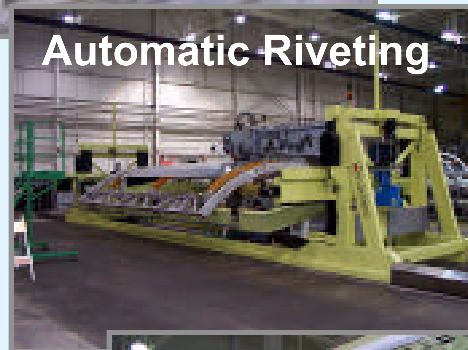
Category	Old Paradigm	New Paradigm
Hard tools	28	0
Soft tools	2/part #	1/part #
Major assembly steps	10	5
Assembly hrs	100%	47%
Process capability	$C_{pk}<1$ (3.0σ)	$C_{pk}>1.5$ (4.5σ)
Number of shims	18	0
Quality (nonconformances/part)	.3 (> 1000)	.7 (<20) *

* Early results with improving trend

747 Precision Skin Panel Assembly Processes
Vought Aircraft Industries

Detail Fabrication

Tack
Details Located By Coord Holes



Riveting
Full Size Fasteners Installed (CNC)

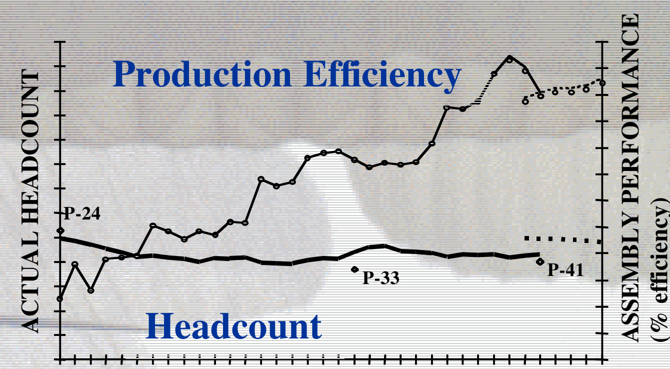
Pick-Up
Final Details Located By Coord Holes

Final Assembly
Skin Panel Assemblies Located By Coord Holes

Skin Panel Assembly

Precision Self Located (Product Flexible)

Customer Practices & Policies
Incentives for Lean Behavior on C-17

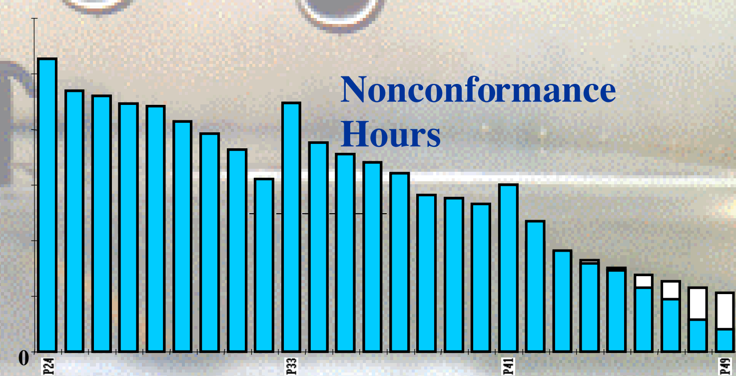


Lean Business Practices

- Strong Integrated Product Teams proponent
- Shared metrics and data
- Creative Incentives
  - Separate contracts to provide insight (delivery, affordability, support)
  - Award fee for each contract tied to complementary goals and measures
  - Unique incentives in multi-year contract (e.g. sell place in line if FMS opportunities arise)

Results

Deliveries ahead of schedule
Production efficiency up 50%
Nonconformance hours down 70%



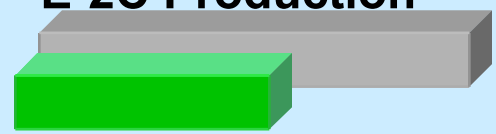
Source: C-17 SPO

Impact of Lean on Throughput Time
Northrop Grumman

Stretch Goals YE 1998 to 2003		Metric	Thru 2000
• Cycle Times	↓	> 50%	22%
• Square Feet	↓	> 25%	25%
• Net Working Capital / Sales	↓	> 15%	44%
• IT Applications	↓	> 80%	15%
• Sites on Common Proc's & Bus. Syst.		100%	0%

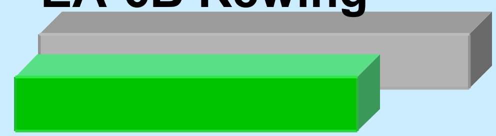
Throughput Time Reduction Examples

• E-2C Production



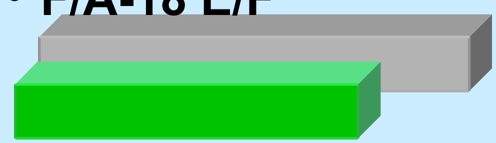
41% ↓

• EA-6B Rewing



21% ↓

• F/A-18 E/F



21% ↓

• Joint STARS

29% ↓

Enhanced Competitiveness and Financial Performance

Requirements

- 25% greater *payload*
- 3 times greater ordnance *bringback*
- 40% increase in unrefueled *range*
- 5 times more *survivable*
- Designed for future *growth*
- Replace the A-6, F-14, F/A-18 A/B/C/D
- Reduced support costs
- Strike fighter for multi-mission effectiveness

Program Execution

- Development budget capped at $4.88B
- Completed on schedule - 8.5 years from “go-ahead” to IOC
- Program was never re-baselined
- *High correlation of Program Management practices and LAI’s Lean Enterprise Model*

Air Superiority | Fighter Escort | Reconnaissance | Aerial Refueling | Close Air Support | Air Defense Suppression | Day/Night Precision Strike | All Weather Attack

Highly capable across the full mission spectrum

Impact of Lean on LAI Stakeholders

Lean Leaders - % Implementation*

% Implementation	
25-40%	Manufacturing
20-30%	Supplier Integration
15-20%	Product Development
2-10%	Business Processes
<10%	Acquisition Interface

Substantial improvements in manufacturing efficiency

Beginning to impact lower tier supply base

Opportunity to increase impact in:

- **Product development**
- **Business processes**
- **Acquisition**

*LAI Integration Team Assessment based on Jan 31, 1999 White Paper

Value - Some thoughts

- Focus of Cold War years was *Performance*
- Focus of 1990s was *Affordability*
- How can we resolve these?
- *Value* encompasses both and can provide a framework for 21st century aeronautical engineering.

Value - Slack's* definition

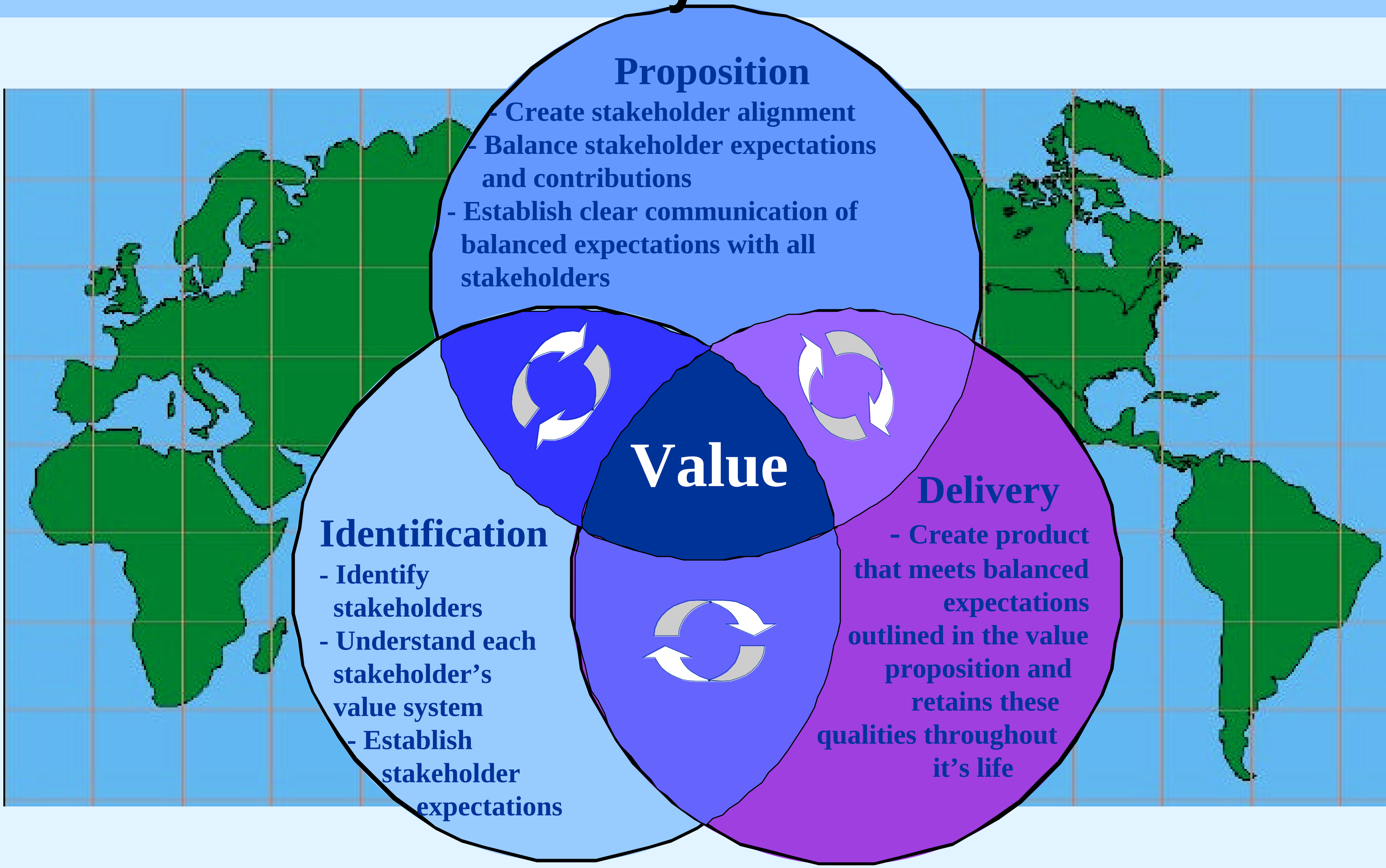
"Value is a measure of worth of a specific product or service by a customer, and is a function of (1) the product's usefulness in satisfying a customer need, (2) the relative importance of the need being satisfied, (3) the availability of the product relative to when it is needed and (4) the cost of ownership to the customer."

(1) and (2) equate to *Better*

(3) equates to *Faster*

(4) equates to *Cheaper*

Theoretical Framework for Lifecycle Value



Value: A Symbolic Representation

$$Value = \frac{f_p(performance)}{f_c(\mathrm{cost}) \cdot f_t(time)} \sim \frac{Better}{Cheaper \cdot Faster}$$

- Similar to definition developed by value engineers (no time function)
- Value defined by the customer for each system or product
- Comprised of specific performance, cost, schedule metrics with weightings representing customer utility functions and normalizations for consistency

Examples of Value Metrics

Performance

- Vehicle performance (range-payload, speed, maneuver parameters)
- Combat performance (lethality, low observable, store capability)
- Ilities (Quality, reliability, maintainability, upgradability)
- System compatibility (ATC, airport infrastructure, mission management)
- Environmental (Noise, emissions, total environmental impact)

Cost

- Development costs
- Production costs, fixed and recurring
- Operation costs
- Upgrade/conversion costs
- Disposal costs

Schedule

- Acquisition response time, or lead time
  - Recognition time
  - Initiation time
  - Product development cycle time
- Order to ship time
  - Lead time
  - Production cycle time
- In-service turn around time

Value provides a multidimensional framework

Risk

- ✈ Risk and Value are inter related
- ✈ Quality of value metric, however it is defined, is related to certainty of its representation
- ✈ Risk management is central to delivering value to the customer
- ✈ Customers demand low risk

Opportunities for risk management R&D

Value - An Emerging Concept

- "Value" is a simple, positive concept which all can relate to
- Provides a framework for multidimensional holistic thinking
- Risk management is important
- Tools for defining, measuring and delivering value are needed
- Value can resolve performance and affordability disconnect

Challenges for Aeronautical Design, Engineering Manufacturing

- Cold War legacies
- Aircraft have dominant designs and are in the specific phase of innovation
- New product concepts must provide superior value, not just superior performance
- Our value systems need to match 21st century realities

Opportunities for Aeronautical Design, Engineering Manufacturing

- Value as a framework for the future
- System level improvements
- New technology for sub-systems
- Improvement in processes can yield improvements in value

Aeronautics provides enormous value to our society.

It is up to us to assure its continued vitality!