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Advanced Manufacturing for Aerospace

A systems approach to understanding additive manufacturing's impact on the aerospace supply chain

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There are three key questions addressed

What are the nuance of additive manufacturing, and why is aerospace unique?

What parts are vulnerable to displacement by additive manufacturing?

How, when, and to what extent will the supply chain be disrupted?

Section 1: *Additive Manufacturing Overview*

Section 2: *Aerospace Overview*

Section 3: *SLS Process Modeling*

Section 4: *Case Study ~ AM Implementation*

Appendix

Section 1

Additive Manufacturing Overview

All major aerospace companies have engaged in some type of additive manufacturing (AM)

Recent Investments in Additive

Source: secondary

AM enables building parts that historically were not possible to machine

Typical Parts from an AM Process

Organic Shape Optimization

Internal Lattice Optimization

AM is the process of adding - as opposed to removing - material to create a part

*Ultimate benefit is ability to **lightweight** a part via topology optimization*

Source: analysis

AM is categorized by material source and energy method, clearly involving benefits/risks

AM Characterization

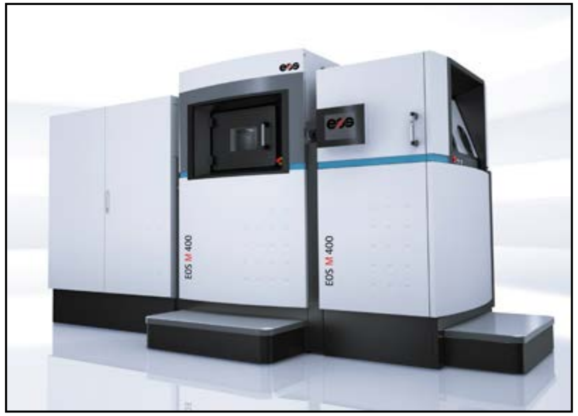
Classification

1) Material source:

- Powder bed
- Powder feed
- Wire feed

2) Energy method:

- Laser
- Electron beam
- Plasma



Aerospace Applications

- Repairs (1980s)
- Tooling (1990s)
- Whole parts (2010s)*

Benefits

- Reduce weight
- Reduce part count
- Reduce lead time
- Increase material yield

Risks

- Microstructure quality
- Process repeatability
- Surface finish

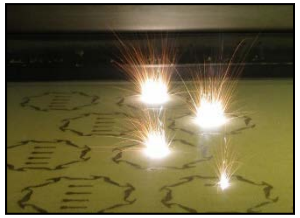
Source: analysis

* Mostly prototyping, not production

Two most common AM "modalities" in aerospace are powder bed and wire feed

Predominate AM Technologies*

Powder Bed – Selected Laser Sintering (SLS)

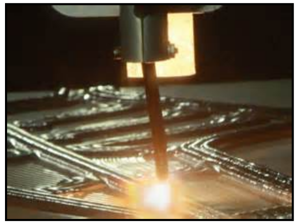


Growing layers via melting/sintering powder metal – developed at UT in 1980s for DARPA

Advantages: high near net, complex geometry

Disadvantages: limited size, small batches, source material control

Wire Feed – Directed Energy Deposition (DED)



Melting wire – similar to welding – to create molten pool to build linear layers

Advantages: high deposition, economical

Disadvantages: more machining, residual stresses, voids/occlusions

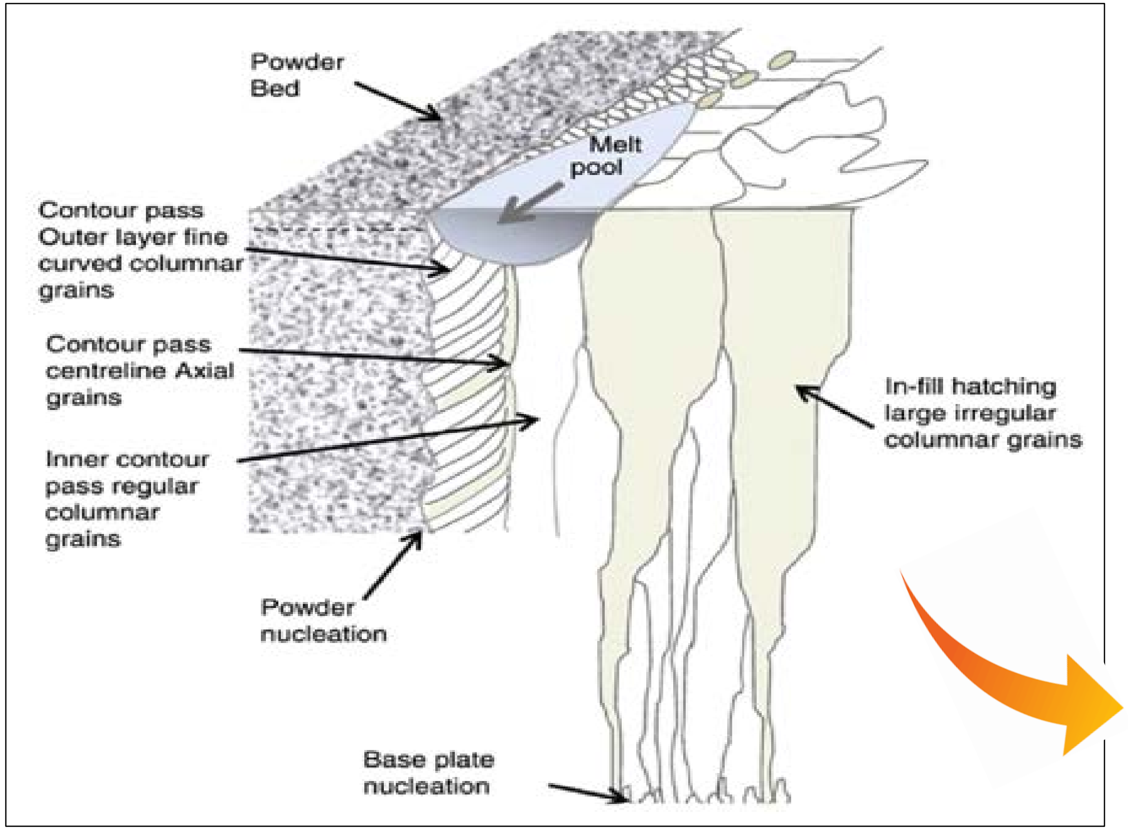
*PB SLS favors **engine** (castings) parts, whereas wire DED basically targets **aerostructures** (forgings)*

Source: analysis, secondary

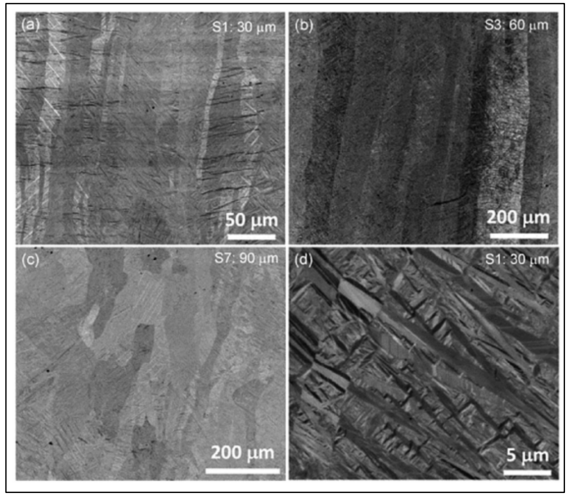
* Powder DED is less common in aviation/aerospace

AM process, however, introduces variability and thus risk into production process

AM Physical Process & Resulting Microstructure



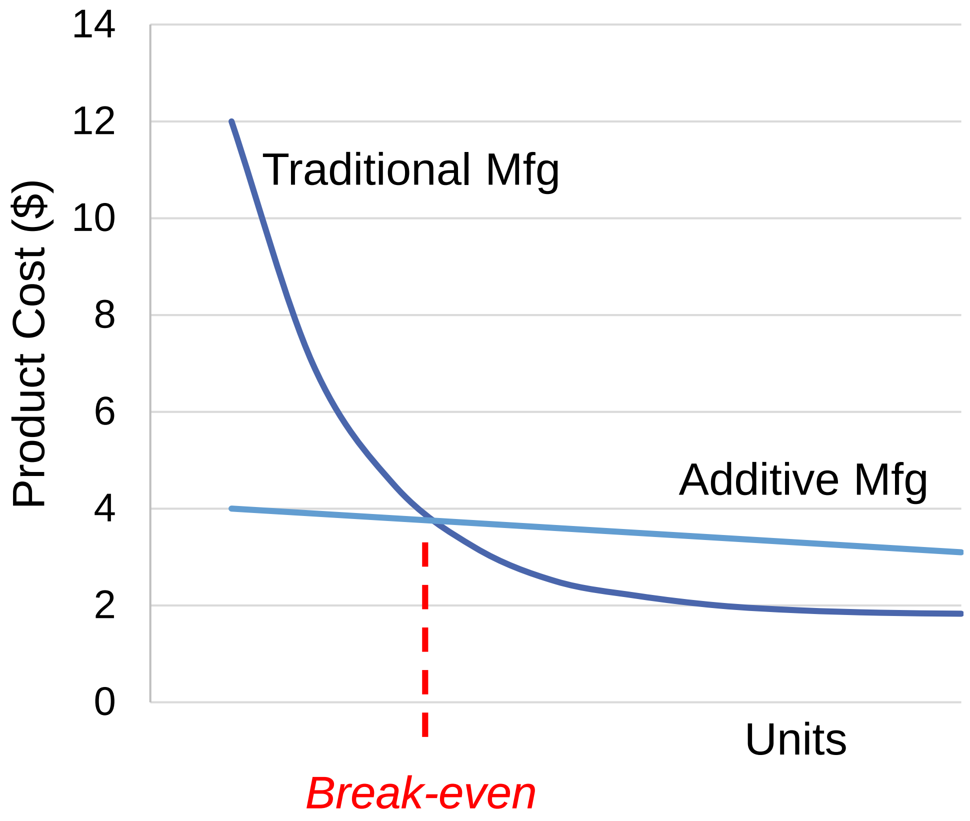
- AM is complex physics process
- Extreme heating/cooling affect gain and mechanical properties
- Aerospace historically uses **isotropic** metals
- Problems such as **creep** and **fatigue** initiated by grain boundaries and surface finish



Source: Herzog et al. 2016

AM parts are economically attractive for “smaller” production runs

Notional Marginal Cost Analysis – Traditional vs AM



- **Molds** (casting) and **dies** (forging) are **expensive** and have long development times
- Thus, economies for these tool/die are realized over long production runs*
- **AM** parts are **less expensive for short runs**
- Break-even also depends upon **part complexity**, thus complicating ROI analysis

Source: secondary

* Includes amortization of initial NRE (non-recurring engineering)

Section 2

Aerospace Overview

Differences between aircraft and automotive effectively define their manufacturing strategies

Aerospace vs Automotive Industry

Units Produced:	4K	10K	60M
Unit Size:	100 to 200 ft^2	5-10 ft (dia)	5 x 15 ft
Part Count:	2.5M	30K	30K
Design Objective:	Airworthiness	Airworthiness	Crashworthiness
Quality Drivers:	Product integrity	Product integrity	Production integrity
Supplier Base:	Duopoly	Oligopoly	Globally competitive

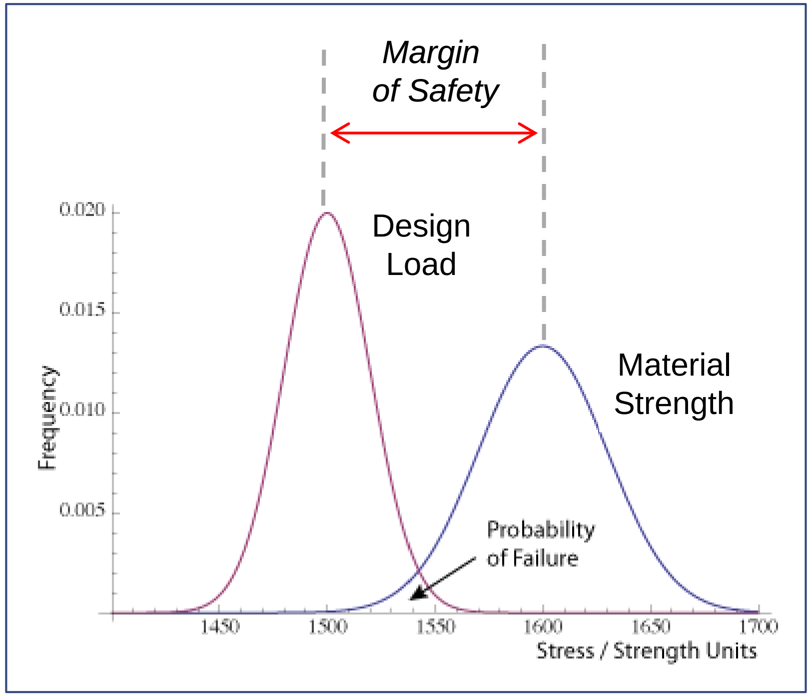
Source: analysis, secondary

* commercial turbine aircraft

Aerospace is unique in part due to lower margins-of-safety due to weight constraints

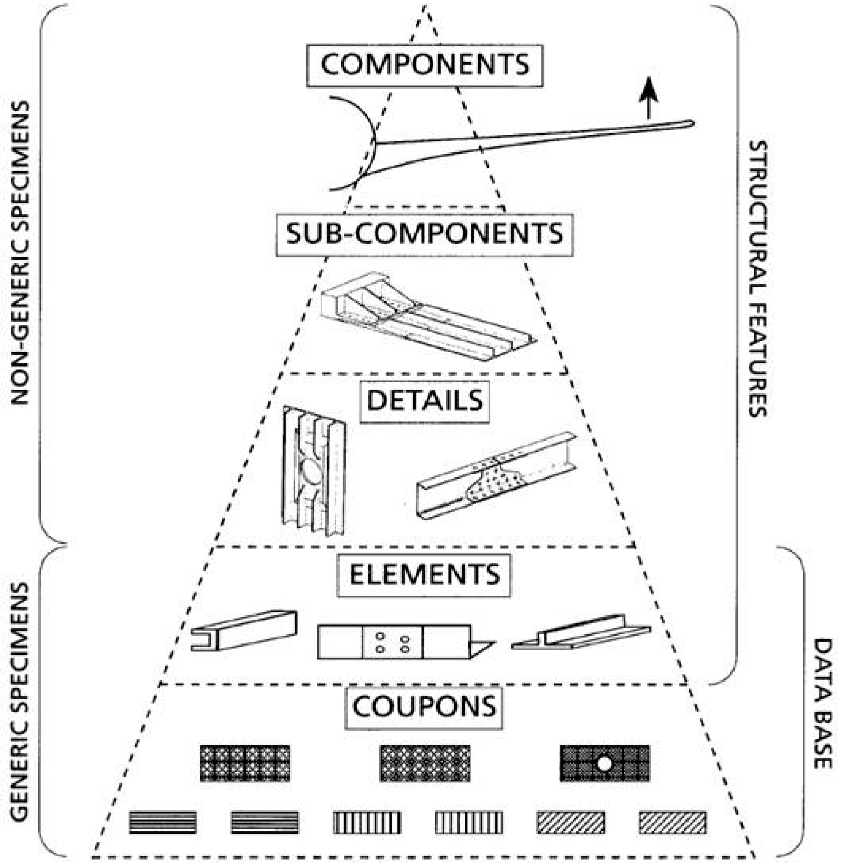
Margin of Safety

- Aircraft designed with margin-of-safety 1.5 to 2 to **minimize weight**
- Automotive uses 3, pressure vessels 4
- This helps minimize fuel consumption
- Thus aerospace has stringent **quality control** and maintenance schedules



FAA certification is costly/arduous to guarantee six-sigma adherence to design and safety

Aircraft Design Substantiation*



- Certification is process of substantiating **both** aircraft **design** and **production**
- Engineering proves structure can withstand anticipated static and dynamic loads
- Testing begins with material samples to identify basic material properties
- In certain cases, full-scale testing is required – expensive both time and money

Source: FAA

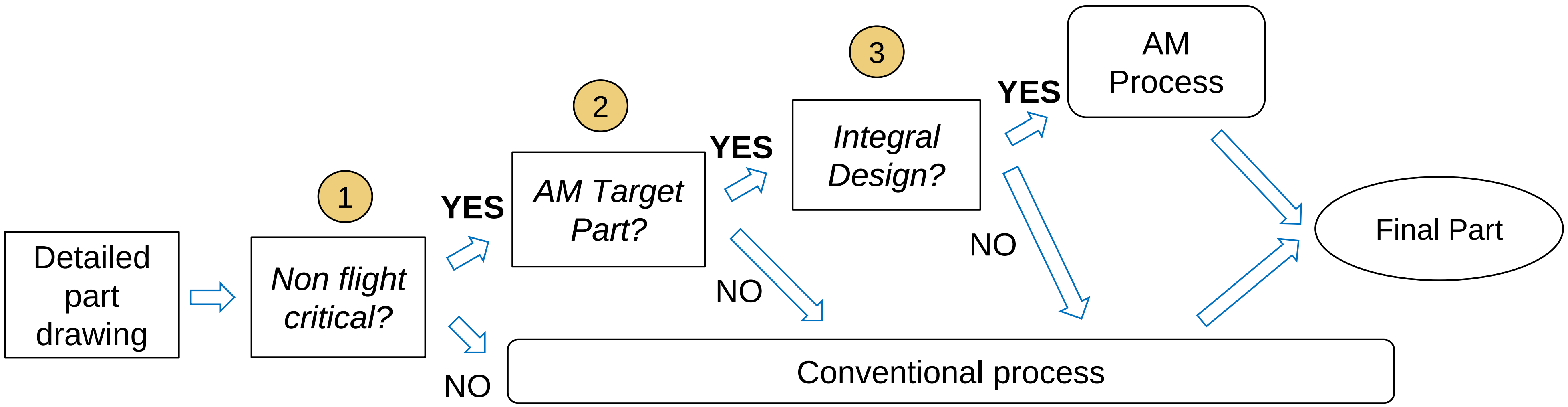
* Others regulating entities include EASA, NASA, DoD

Section 3

SLS Process Modeling

There are three fundamental decisions to determine a part's candidacy for SLS AM

SLS AM vs Casting Decision Analysis for Early Adoption



1 Is the part **flight critical**?*

2 Does the part conform to: **small**, **complex** and **small lot**? ⇦ *Critical for Powder Bed SLS*

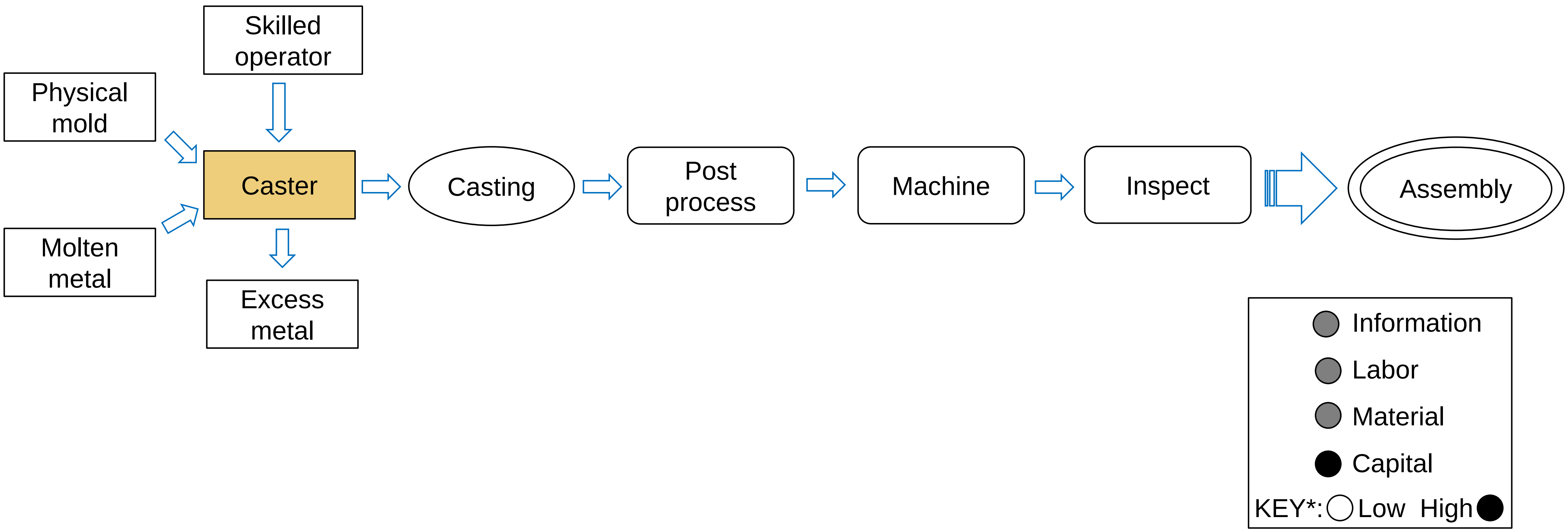
3 Can we safely assume comparable **material characteristics**? ⇦ *Uncertainty Quantification*

Source: analysis

* Avio's TI-AL LPT blades serve as a strong counter example

Casting is a multi-step process, which ultimately require final assembly for complex parts

<u>Simplified Casting Scheme</u>

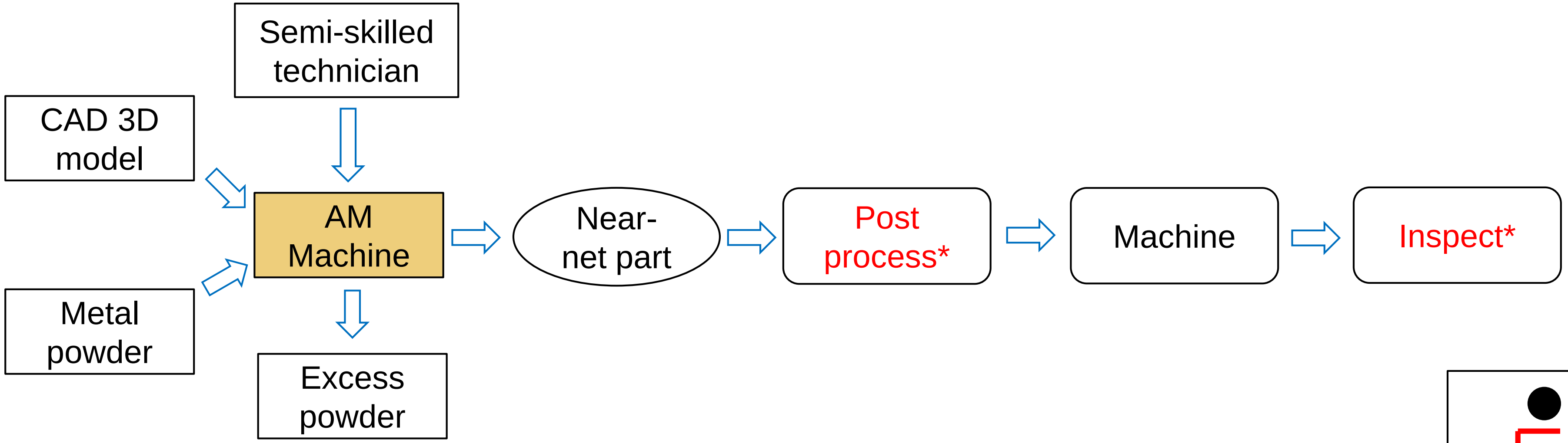


Source: analysis

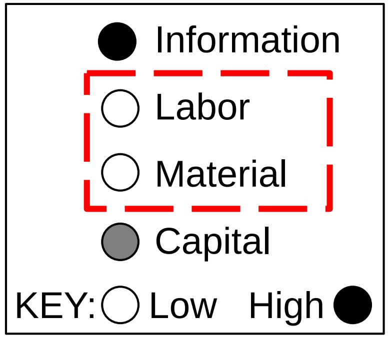
* Loosely compared to forgings

…whereas *for "targeted" parts*, AM SLS can make complex assemblies more readily

<u>Simplified SLS AM Scheme</u>



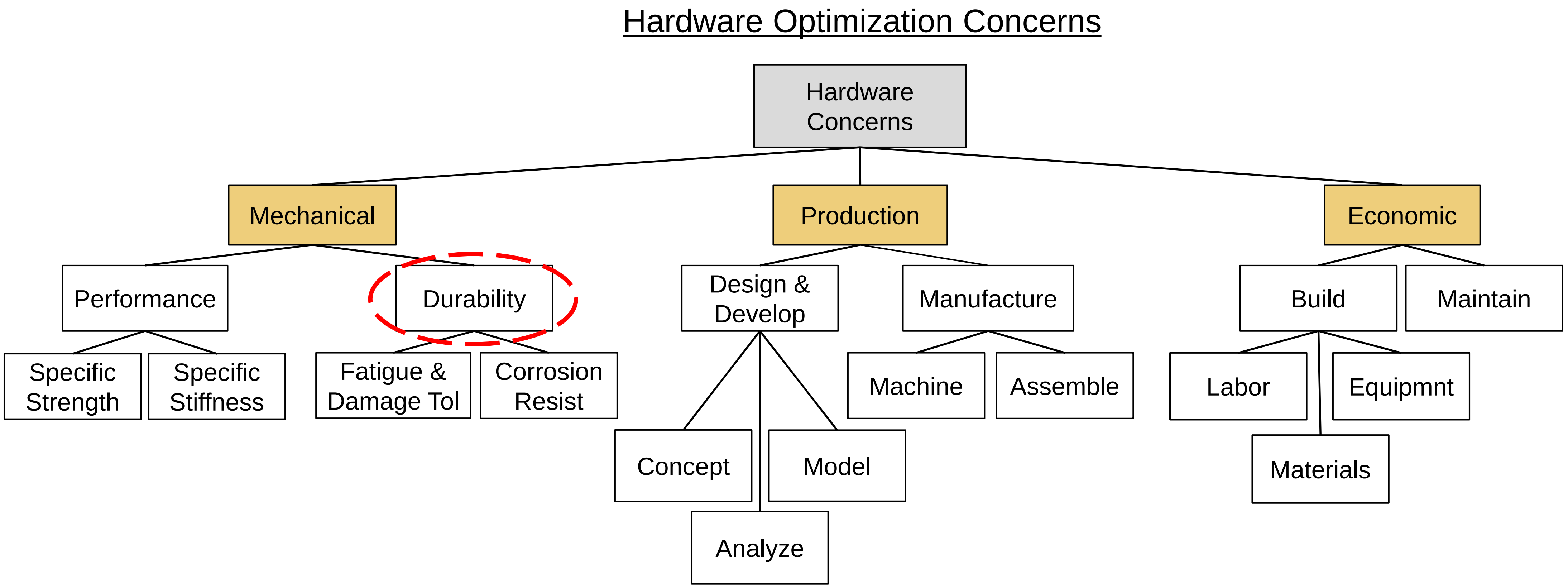
AM is known as more labor and material efficient



Source: analysis

* Red – more intense/scrutinized process

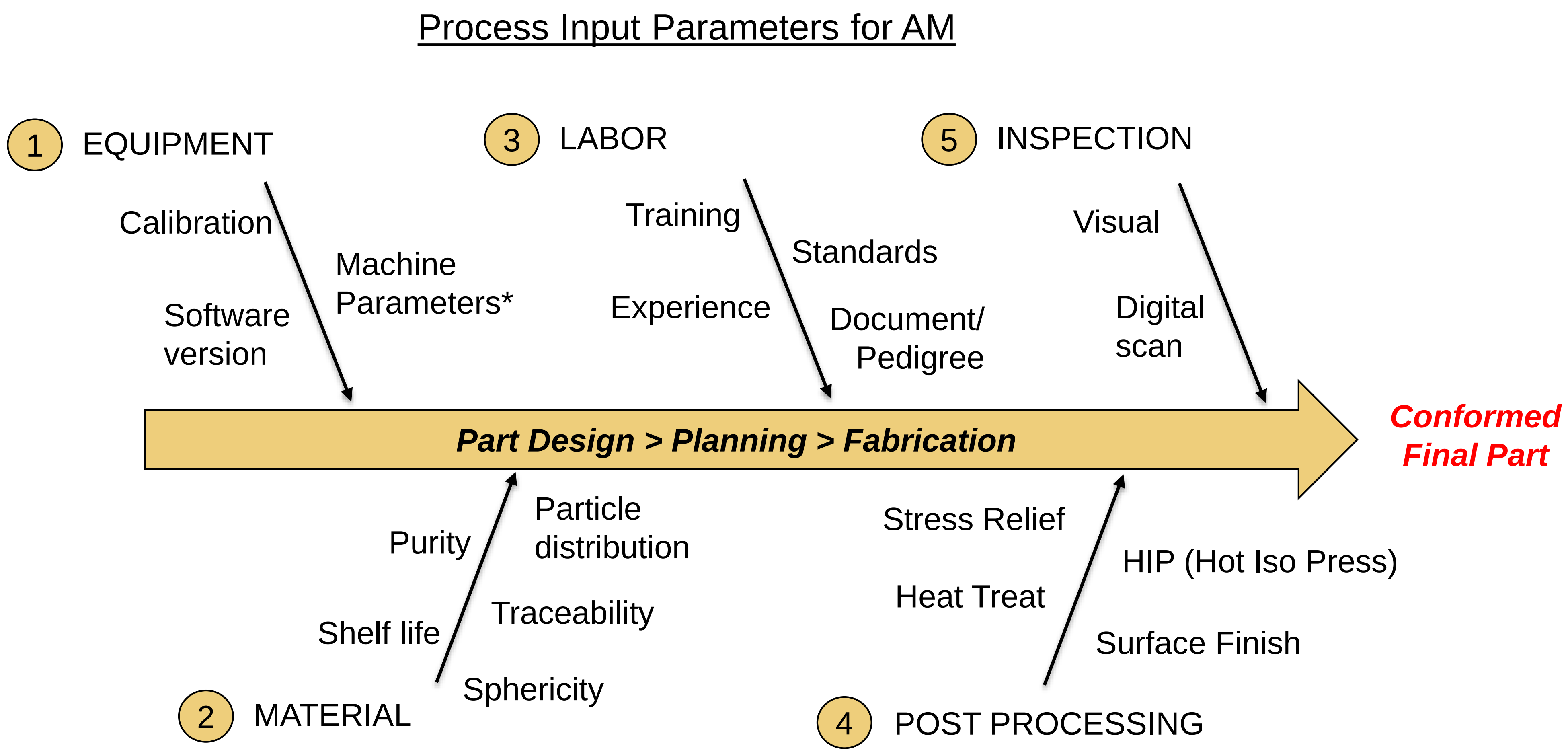
Business case needs to consider economics and production efficiency vs mechanical properties



The most important consideration for AM aerospace parts is ***integrity to ensure safety*** *over the life of the asset*

Source: analysis

Nonetheless, multiple variables – some unique to AM – complicate understanding of properties



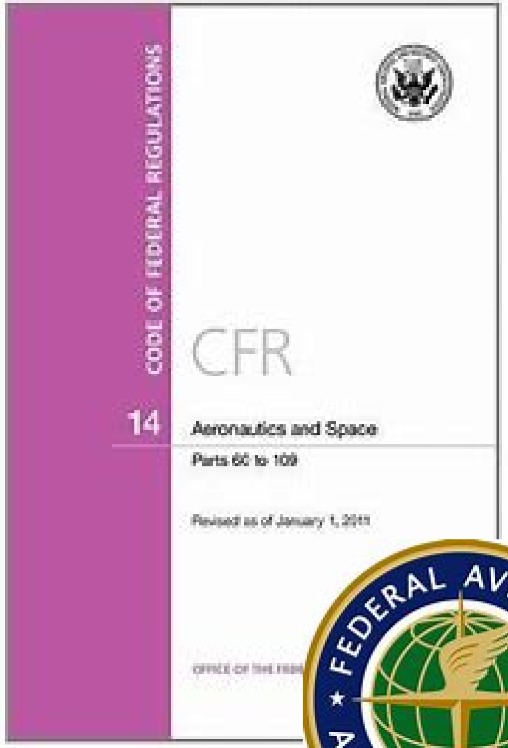
Source: analysis

* Includes laser intensity, hatch pattern, sweep rate, etc.

FAA currently lacks specific guidelines for AM part qualification – most companies use “point design”

AM Part Substantiation

- FAA 14 CFR specifies new parts/process be qualified via testing: 2X.603 (*Materials*), 2X.605 (*Fabrication*), and 2X.613 (*Design Values*)
- However, FAA has not yet established an acceptable generic means of compliance of AM parts – an Issue Paper is a common*
- Applicants outline means of compliance to control material and process variation, then use “point design” and **qualify by testing**
- MMPDS Emerging Tech Work Group is developing AM guidelines
- Solution will likely combine: a) process controls and validation, b) damage tolerance framework, and c) sophisticated NDI methods



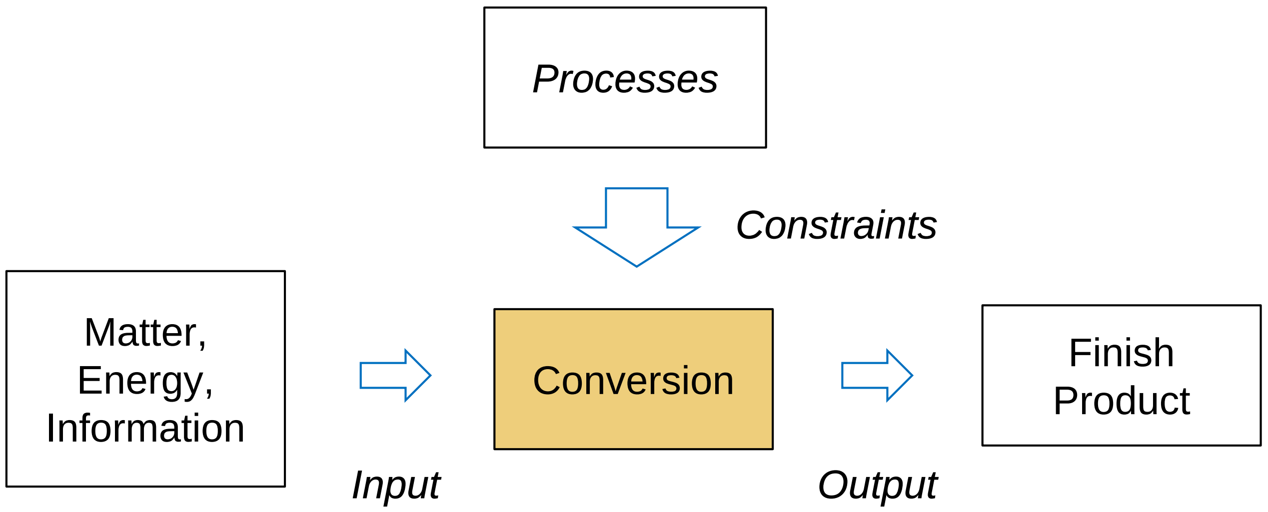
* NASA offers MSFC Std & Spec 3716 & 3717

Section 4

Case Study: AM Implementation

A simplified framework helps identify elements necessary for systems modeling

<u>Rudimentary Systems Schematic</u>



GE's new turboprop – which is 35% printed – is used as a case study

GE's New Advanced Turboprop

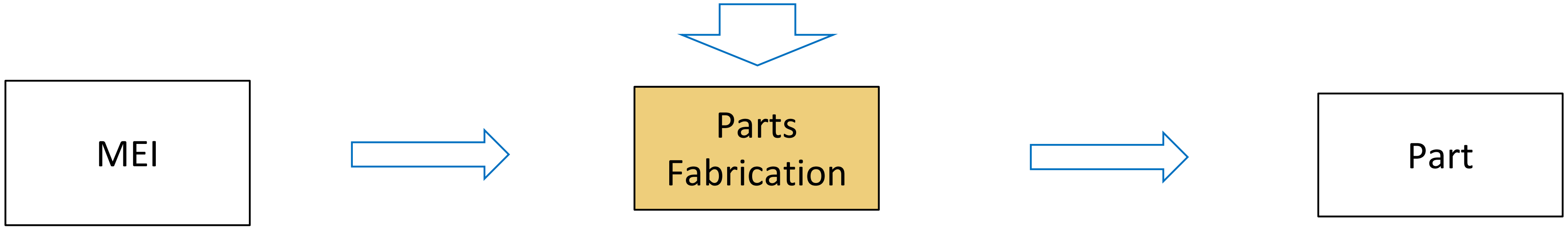
- GE prints 35% of new gas turbine in 1000-1600 SHP class
- Over **850 parts replaced by 12**, mostly castings*
- Parts includes: cases, frames, comb liner, heat exchangers
- AM parts reduced weight by 5% and contribute to 1% improvement in specific fuel consumption (SFC)
- Moreover, a similar GE engine redesign using AM **eliminated 10-15 suppliers** typically required
- Overall PLM costs can be significantly reduced

Source: company website, ASME

* Static only (i.e. no LLPs)

Analyzing trade-offs require comparing similar work-steps for castings vs AM…

<u>Casting vs AM Process Resource Utilization</u>



	Casting	AM
Information	●	○
Labor	◉	●
Material	◉	●
Capital	◉	○

	Casting	AM
Create mold vs Prep job	○	●
Pour mold vs Print part	◉	●
Remove part	●	◉
HIP & Heat Treat	◉	○
Machine	◉	●
Surface Treat	◉	○
Inspect	○	○
Assemble	◉	●

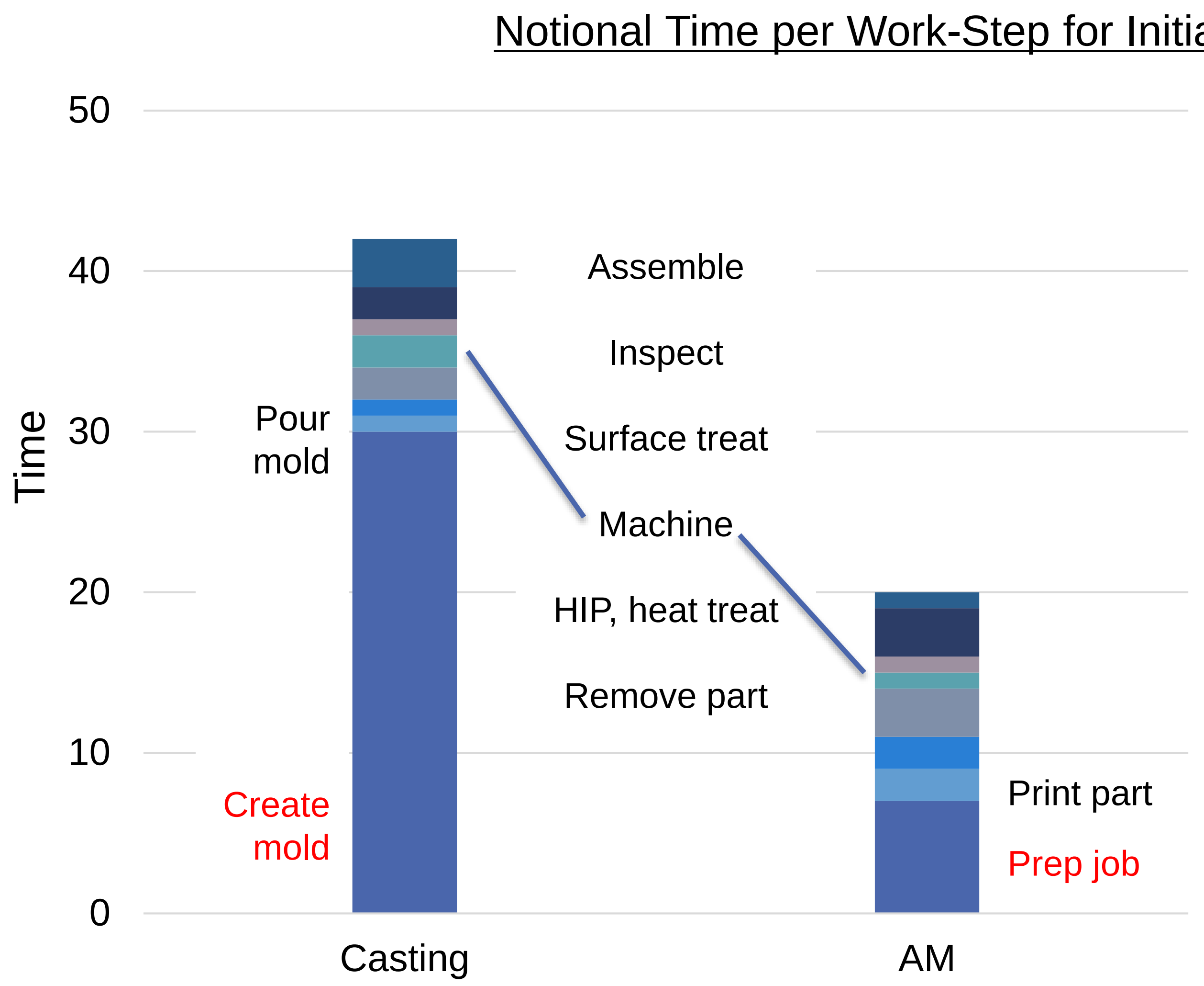
	Casting	AM
Weight	◉	●
Process time	○	●
Material yield	◉	●
Asmb cmplx	◉	●
Predictability	◉	○

KEY*: ● Better
◉
○ Worse

* Process loosely compared to forgings

Source: analysis

… these steps then are viewed in light of amount of processing time



- For “moderately” complex castings, creating molds/tooling can take from weeks to months
- Creating molds/fixtures is the most time intensive and is the most variable step
- For initial production, AM parts can be produced at least twice as fast as castings

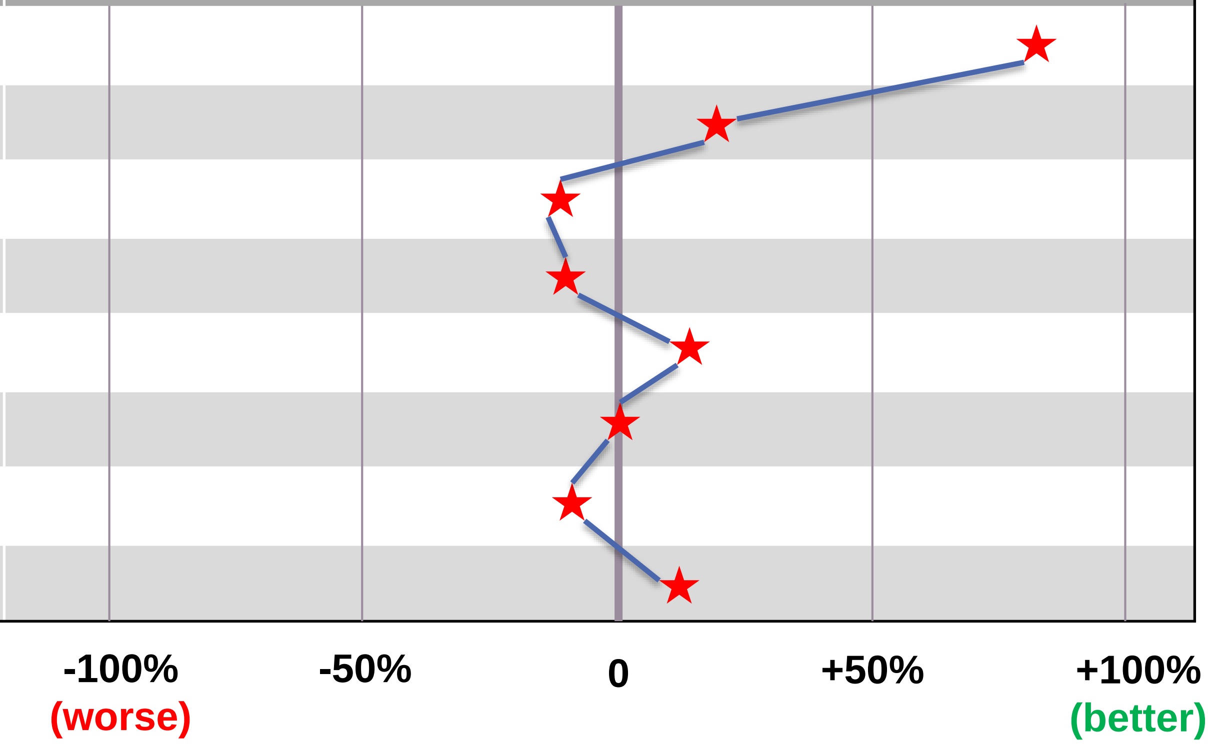
* Assumes CAD model is available; ignores design iterations for AM

Source: analysis, interviews

AM will greatly impacted mold creation, though other functions will likely not be materially affected

Anticipated Impact on Resources & Suppliers – Casting vs AM

Work-Step	Casting	AM	Resource Net Change
Create mold vs Prep job	Foundry	OE/SB*	
Pour mold vs Print part	Foundry	OE/SB	
Remove part	Foundry	OE/SB	
HIP & Heat Treat	3rd party	3rd party	
Machine	OEM/3pty	OE/SB/3pty	
Surface Treat	3rd party	3rd party?	
Inspect	OEM	OE/SB	
Assemble	OEM	OE/SB	



Source: analysis

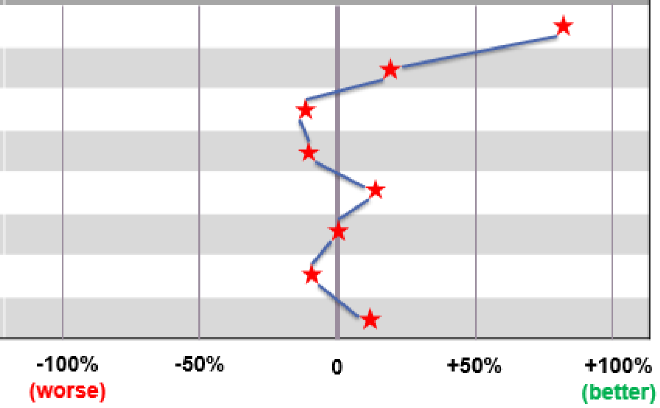
* OEM or major Service Bureau

Thus, foundry market share will decrease, but other tier suppliers will be much less affected

<u>Summary of Impact of AM Parts and Suppliers</u>

- AM's greatest advantage is lack of tooling; this, along with 'insourcing', will eventually impact foundries' market share
- The mold pour process is labor intensive and dangerous, requiring firing the ceramic shell

Work-Step	Casting	AM	Resource Net Change
Create mold vs Prep job	Foundry	OE/SB*	
Pour mold vs Print part	Foundry	OE/SB	
Remove part	Foundry	OE/SB	
HIP & Heat Treat	3rd party	3rd party	
Machine	OEM/3pty	OE/SB/3pty	
Surface Treat	3rd party	3rd party?	
Inspect	OEM	OE/SB	
Assemble	OEM	OE/SB	



- Interestingly, CNC machine shops will likely not be impacted since: a) castings require little machining, and b) most machining of engine parts is conducted internally
- AM will possibly require <u>more</u> regular inspection (e.g. X-ray, FPI, visual, dimensional) to reduce uncertainty

AM will impact foundries yet timeline is at least a decade hence for meaningful parts production

Conclusion of Impact of AM in Aerospace

- AM can achieve an optimized part, yet **material characterization is difficult** due to the unpredictability of the build
- GE's advanced turboprop illustrates potential impact of AM in aerospace, **targeting engine structural castings**
- A systems model predicts **considerable impact on foundries** but not CNC machine shops as many believe
- **Significant adoption is likely 10-15 years** due to lack of technology maturity as well as new engine platforms

Appendix

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