Rubble to Rockets (R^2)

Hunter Martin

Industry Day Briefing – Program Overview

Breaking the Point of Need Production Paradigm

Briefing prepared for R^2 Industry Proposers

18 March 2024

DARPA

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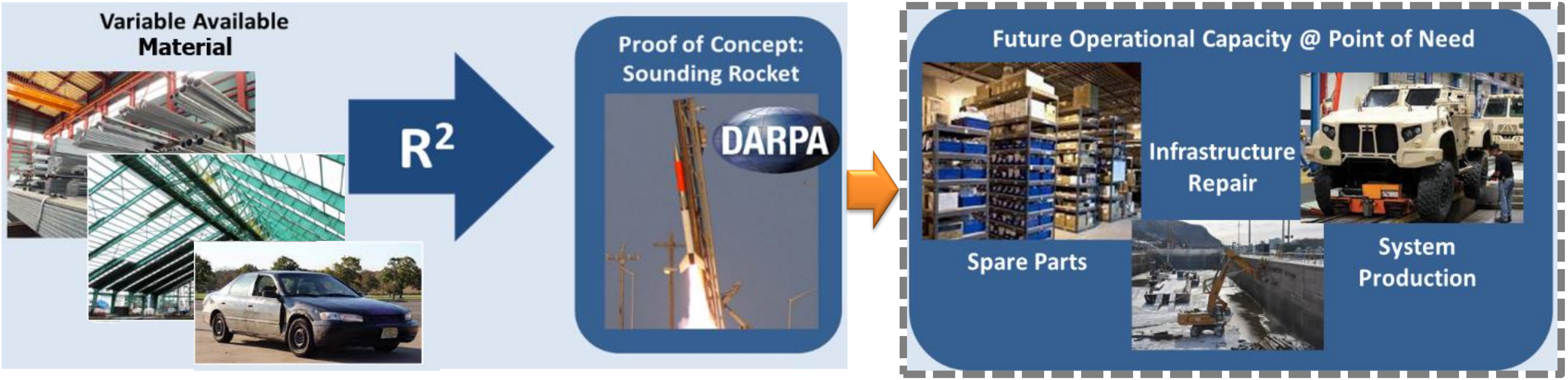
Structures Out of Anything, Made Anywhere, at Many Sizes



Scavenged Feedstock Conversion into Functional Feedstock + Material Characterization + Analytical framework for Rapid Redesign

↓

Point of need manufacturing from any available material

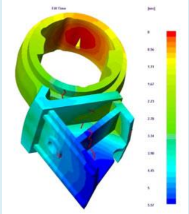
Existing Manufacturing Requires Stability

Current Paradigm: Standard Acquisition

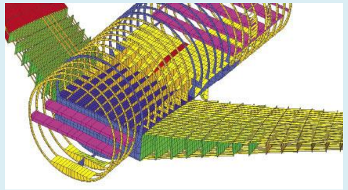
Fixed Materials and Processing

MMPDS-2023
Volume I: Conventional Materials and Joint Allowables

Component Design



System Analysis



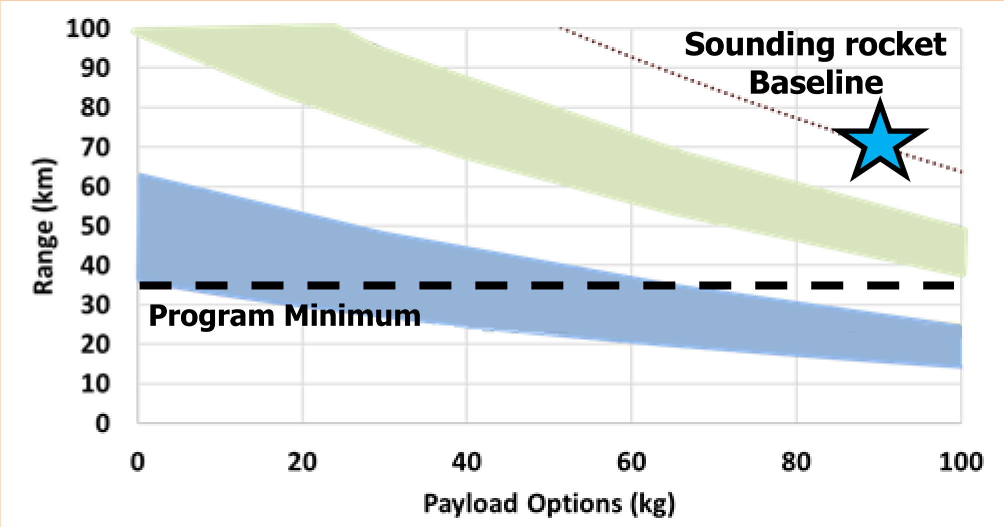
Fixed Design

- **Months to years of design**
- **Single changes can restart process**

Manufacturing at the Point of Need

Unknown or Variable Materials

How to access new design space?



Range $\propto \sigma_y \ln M_f / M_e$

MMPDS: Metallic Materials Properties Development Standardization
kg; kilograms
km: kilometers

M_f : Mass full
M_e : Mass empty
σ_y : Yield strength

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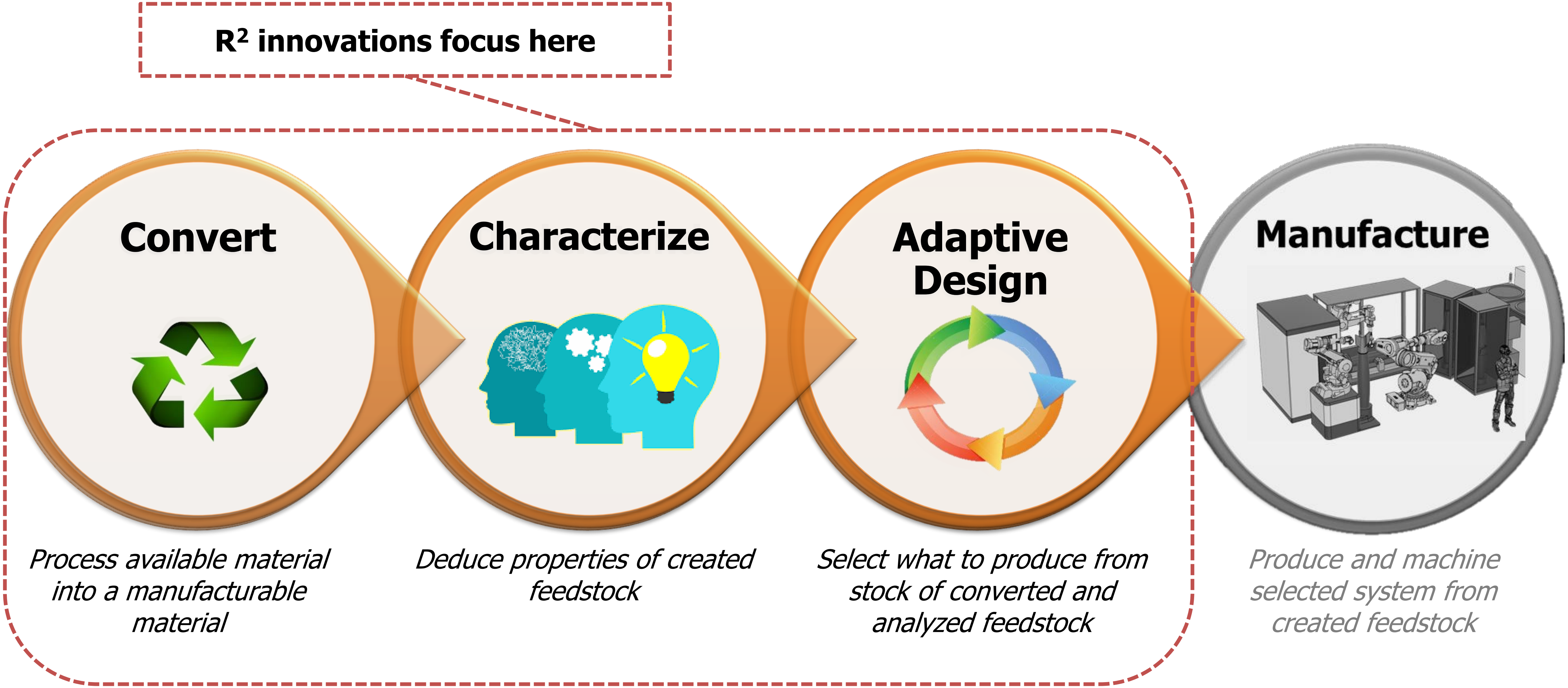
Embracing Variability to Rearm on the Battlefield



R^2: Rubble to Rockets

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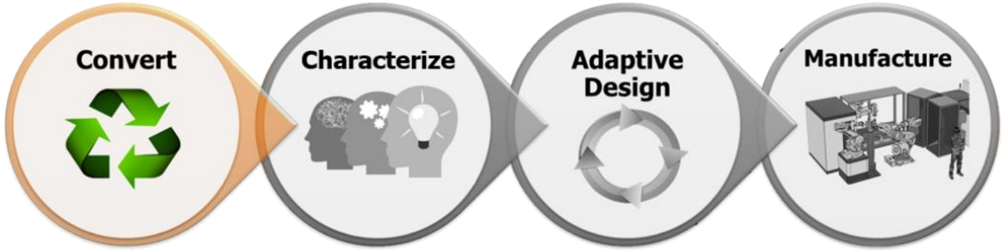
Conversion: Managing Variable Scrap Streams with Targeted Feedstock Output



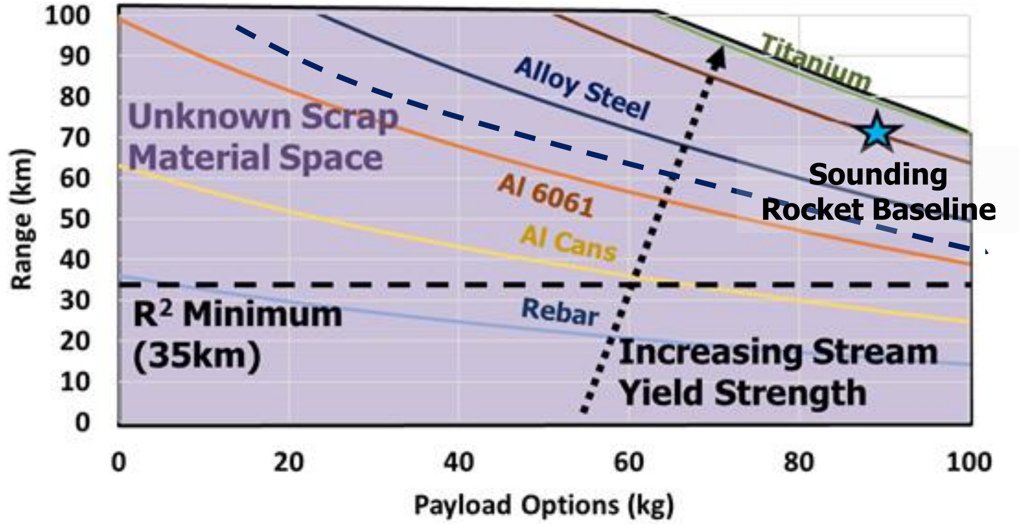
Move away from “clean” material and advance into **processing less curated** and additional scavenged streams (e.g., glass, ceramics, polymers, mixed composition)

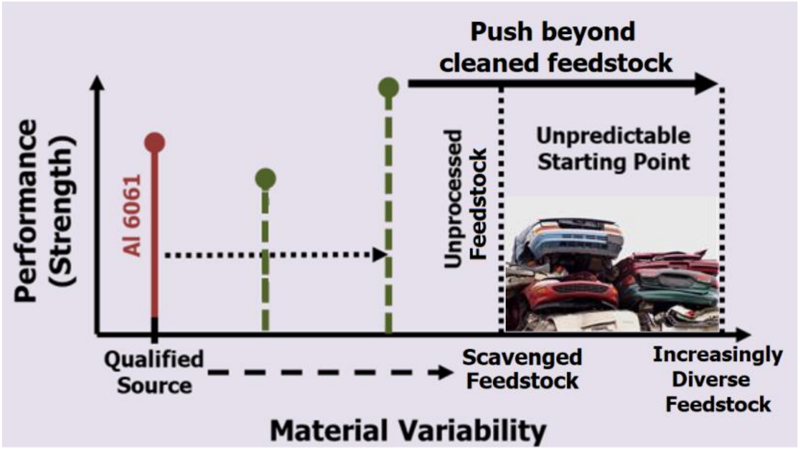
Processing

Direct conversion to feedstock for deployable manufacturing

High Rate (0.1 m³/day) Single Step Conversion
(~300 kg of Al/day)

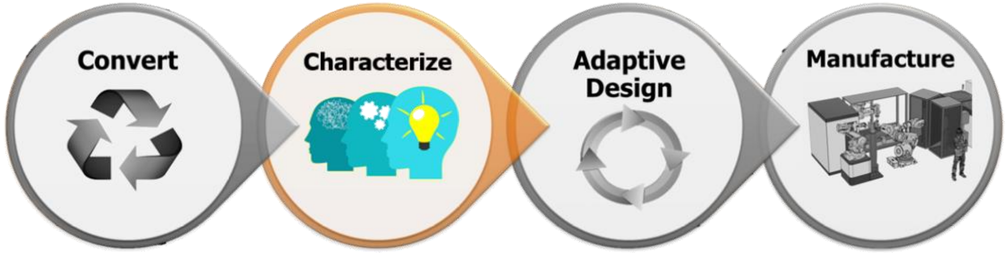
Upcycling to enable highest possible material properties.





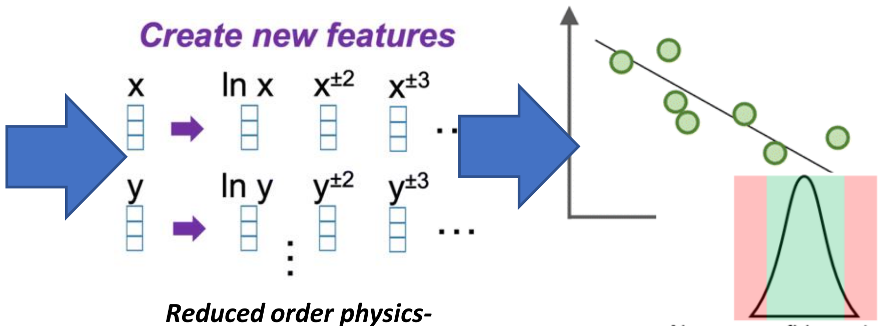
R^2: Rubble to Rockets
km: kilometers
kg: kilogram
m: meter
Al: Aluminum

Understand: High Confidence in Material Properties



Embracing and Understanding Error in Material Characterization

On-line process analysis with non-destructive deployable testing



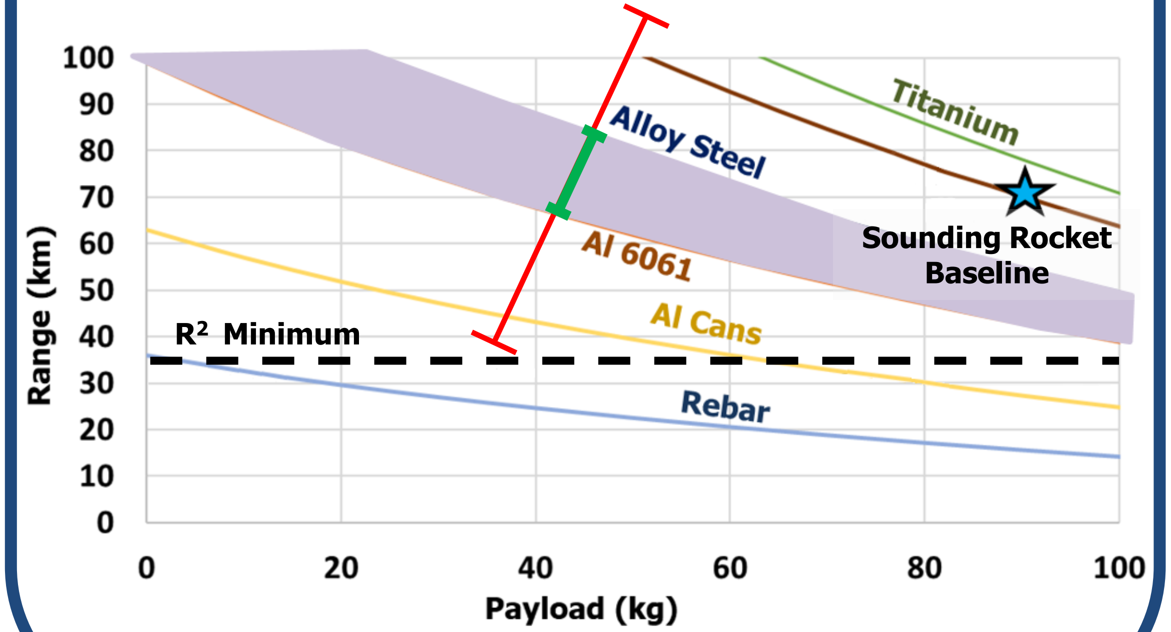
Reduced order physics-informed feature generation

Narrow confidence interval

Muckley, E. S., Saal, J. E., Meredig, B., Roper, C. S., & Martin, J. H. (2023, August 21). *Interpretable models for extrapolation in scientific machine learning*. Digital Discovery.

Utilize minimal data points to **predict material performance** with minimal error to **enable adaptive design**

Error reduction to provide useable material property prediction for design



Minimize error in material property prediction.
Normalized standard deviation for σ_y<0.2 and E<0.05

Al: Aluminum
km: kilometers
kg: kilograms
R^2: Rubble to Rockets

σ_y: Yield strength E: Elastic Modulus

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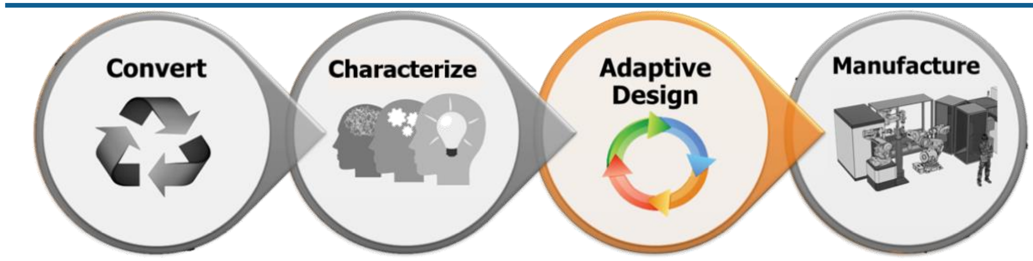
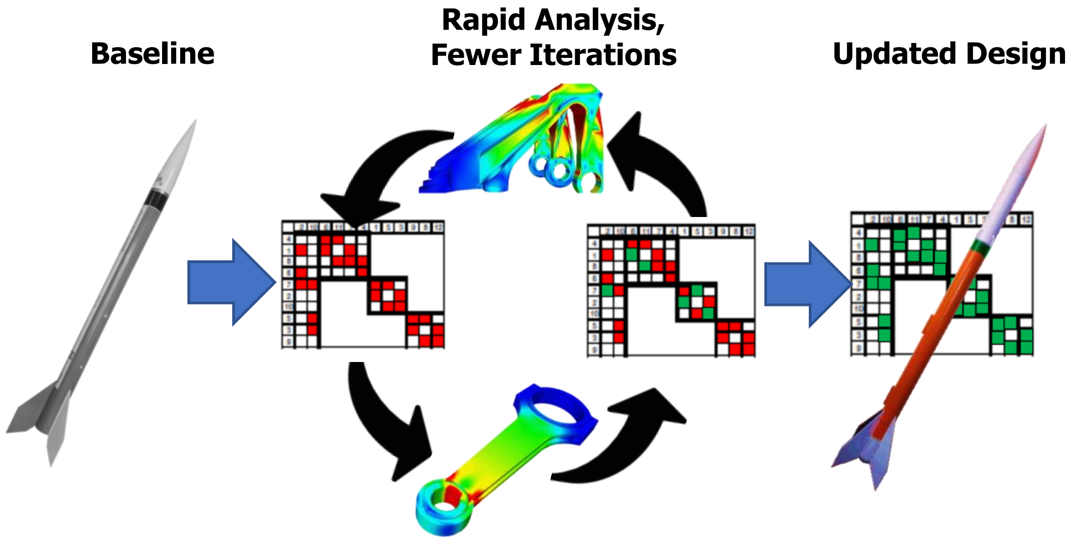
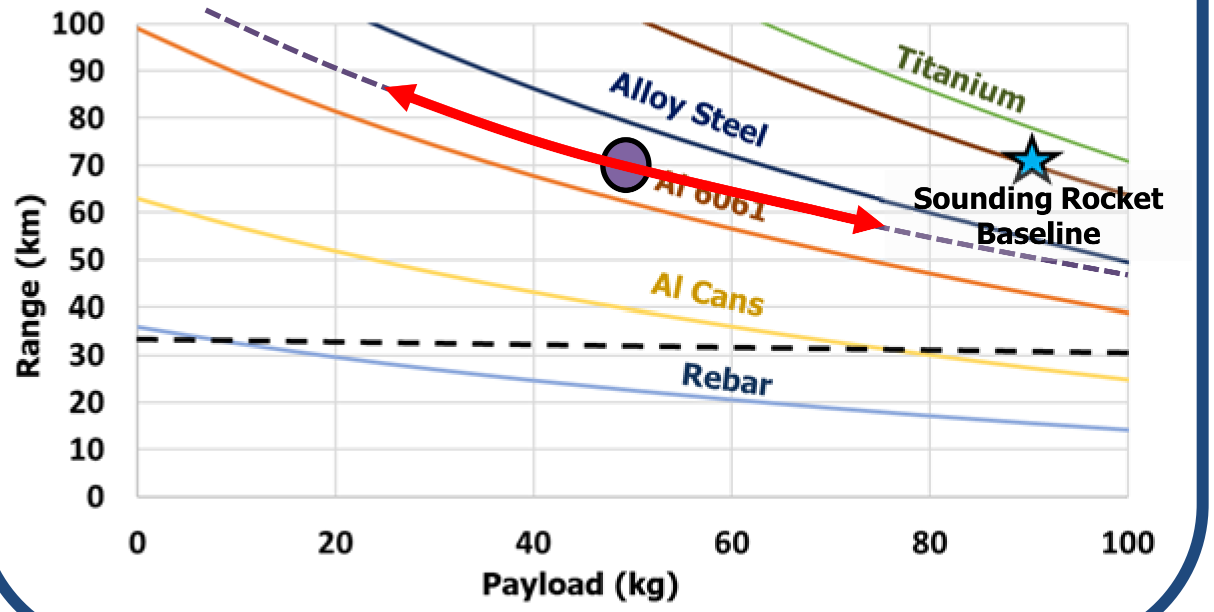
Adaptive Design: Low C-SWAP Flexibility and System Performance Prediction



Rapidly assess **impacts of material change** on performance and develop tools to **modify baseline** design to utilize available materials



Trained, low C-SWAP, adaptive design framework enables redesign to achieve tactically relevant range and payload



Demonstrate rapid (<1 day) adaptive design for ≥35 km minimum range and ability to vary range by ≥25 km for given material

Al: Aluminum
C-SWaP: Computational - Size, Weight, and Power
kg: kilograms
km: kilometers
R^2: Rubble to Rockets

R^2 Metrics

Convert
Can you process the scavenged feedstock given into a manufacturable material?

Characterize
Do you understand the material properties of the feedstock you created?

Predict with **low error** yield strength and elastic modulus

Adaptive Design
Can you produce a feasible design with tailored range and payload fraction?

Update designs for minimum and variable range

Confirmation of manufacturing capabilities with a representative **burst pressure test**

Metrics			
		Phase 1	Phase 2
Material Property Prediction			
	Yield Strength, σ [Stdev/avg]	0.2	0.1
	Elastic Modulus, E [Stdev/avg]	0.1	0.05
	Domain of Applicability*	≥ 2 pristine material streams	≥ 2 material streams
Adaptive Design Tool			
	Range Flexibility	15 km	25 km
	Design Close-out >35 km	< 1 week	< 1 day
Burst Pressure**			
	Pressure	20 MPa	35 MPa
	Duration	10 min	

Contraints	
Scavenged Material Utilization***	0.1 m^3/day
Range	≥ 35 km

* From government determined scavenged feedstock streams, performers must identify a domain of applicability in which metrics can be retired. Government will define feedstocks based on their ability to be indigenously scavenged

** 270mm vessel produced from performer selected domain of applicability

*** Demonstration of capability at subscale sufficient

Avg: Average
E: Elastic Modulus
km: kilometers
m: meters
min: minute
MPa: Mega Pascal
R^2: Rubble to Rockets
Stdev: Standard Deviation
σ: Yield strength

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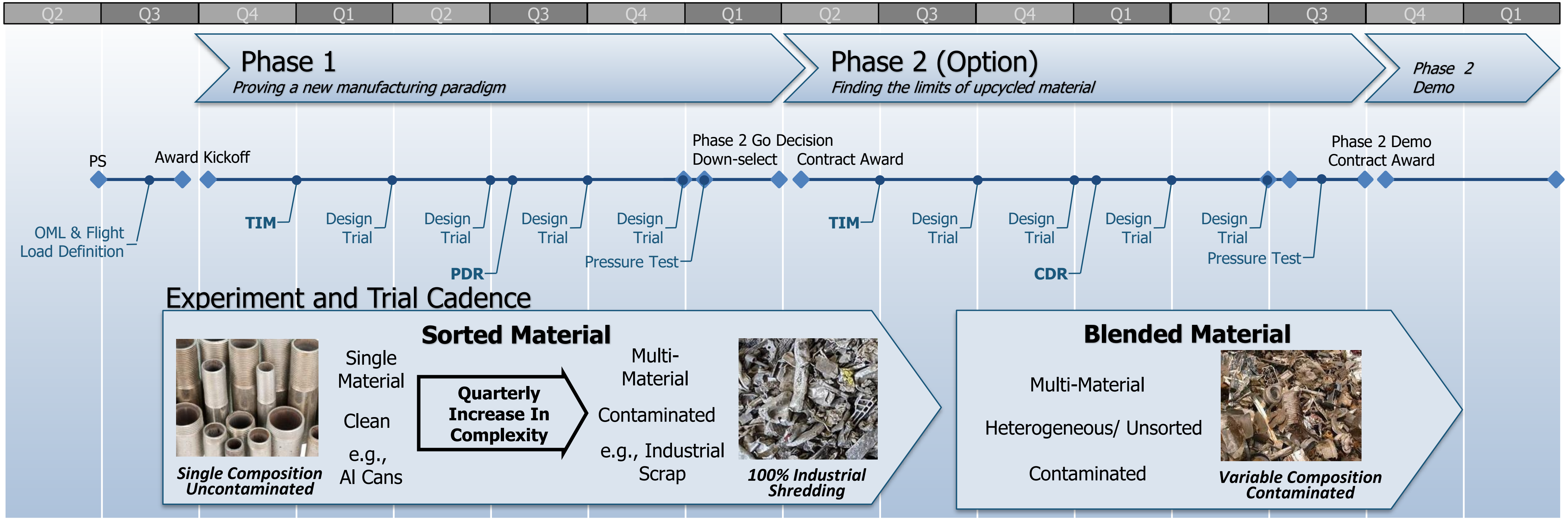
What R^2 is NOT about…

- ✗ TEL-on-demand type of capability; solutions should be deployable in a reasonable capacity
- ✗ Development of new forward deployable manufacturing cells for metallic or plastic FDM; leverage existing technology as applicable
- ✗ Full characterization of material properties; efficiently identify a lower bound design value with high confidence in minimum values
- ✗ Framework that is only capable of producing singular point designs for a given material

CONOPS: Concept of Operations
FDM: Forward Deployable Manufacturing
R^2: Rubble to Rockets
TEL: Transport, Erect, Launch

R^2 Program Plan



An aggressive schedule encourages rapid evolution and iteration, while pushing the boundaries of adaptive designing in conjunction with material conversion and analysis.

Al: Aluminum
CDR: Critical Design Review
OML: Outer Mold Line
PDR: Preliminary Design Review
PS: Program Solicitation
TIM: Technical Interchange Meeting
TRR: Test Readiness Review

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ShAPE Technology Overview

What is ShAPE^{tm}?

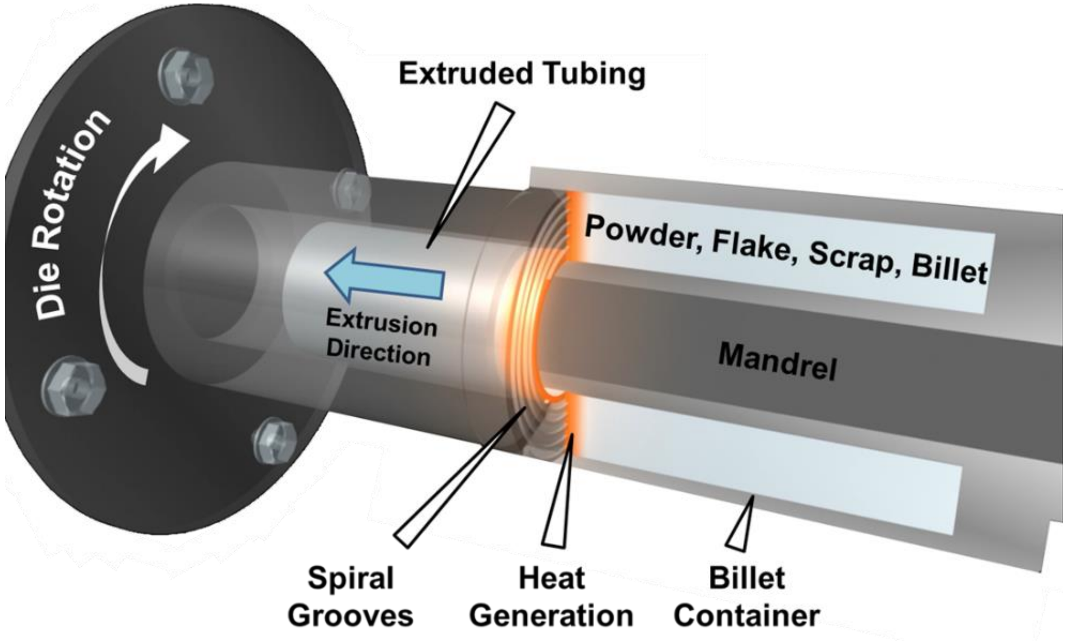
- **Sh**ear-**a**ssisted **P**rocessing and **E**xtrusion is a manufacturing process capable of manufacturing high performance extruded products using various scrap-based feedstock form factors.

How is ShAPE different?

- Severe deformation imparted by billet rotation results in heat generation, grain refinement and redistribution of oxide and secondary phases within the matrix.

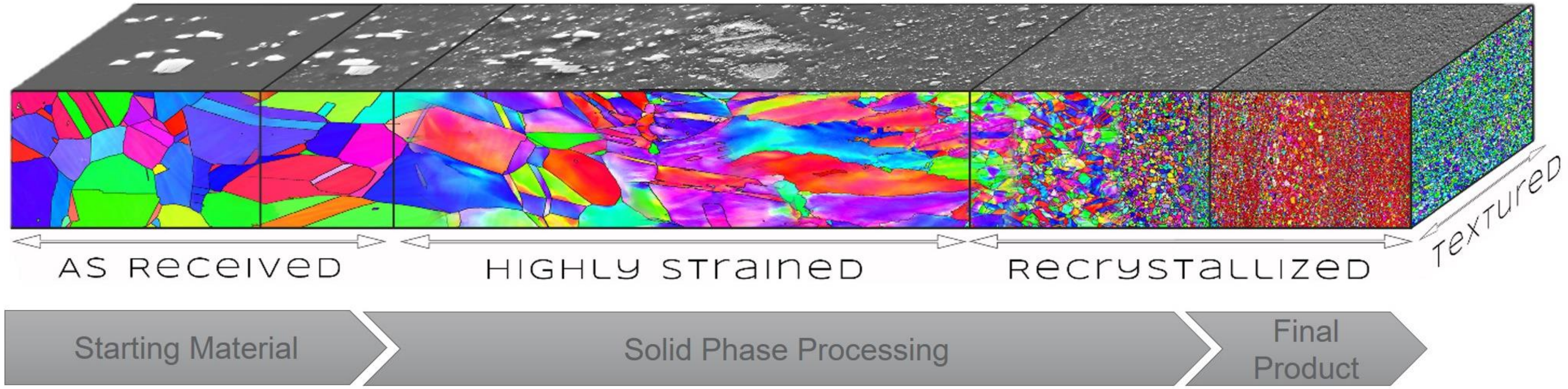
What are the benefits of ShAPE?

- Solid phase processing enables use of a broad range of feedstock materials and form factors to manufacture functional product which achieve necessary strength and elongation requirements.



What makes ShAPE different ?

- Thermal energy or heat is generated in-situ to the process vs a precursor preheating step, typical to conventional extrusion.
- Only a small volume of material is processed at any one time, resulting in a high thermal gradient and minimal heat loss.
- The combination of high shear strain and elevated temperatures facilitate dispersion of oxide and secondary phases, diffusion and phase transformations, eliminating the need for homogenization heat treatment, and increase in ductility.



Elapsed time from start to finish is < 1 minute

Scrap & Briquette -> Al Extrusions
Comprised of Pre- and Post-Consumer Scrap

Post-Consumer Twitch Scrap

\+

Pre-Consumer 6061 Industrial Scrap

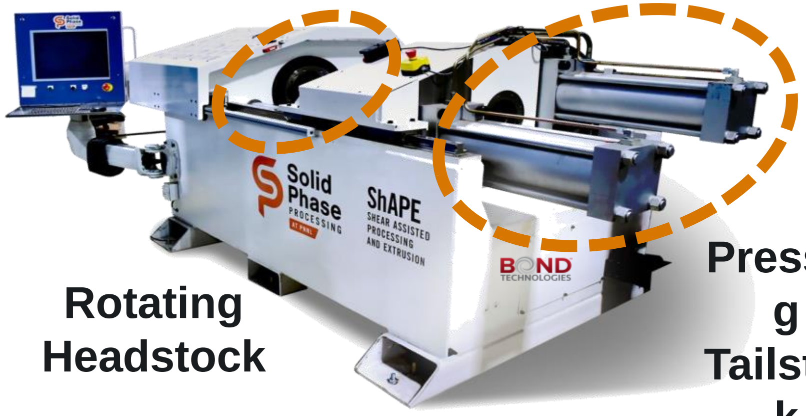
Compacted Briquettes
- 100% Twitch
- 75% Twitch + 25% 6061
- 50% Twitch + 50% 6061

ShAPE Extrusion

Commercially Available ShAPE Machinery

ShAPE 1.0 (2107)

- **Power** = 50 kW
- **Torque** = 3,000 Nm
- **Ram Force** = 900 kN



Rotating Headstock

Pressing Tailstock

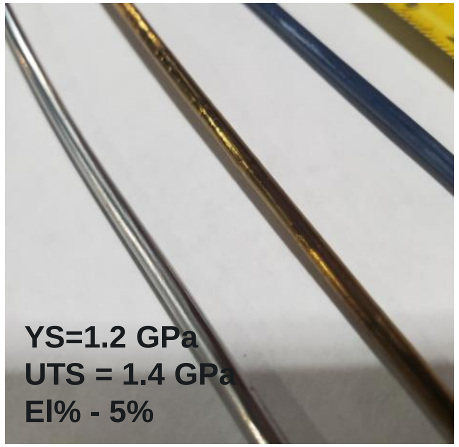
ShAPE 2.0 (2024)

- **Power** = 150 kW (3x)
- **Torque** = 12,000 Nm (4x)
- **Ram Force** = 1,350 kN (1.5x)

ShAPE 1.0 and 2.0 machinery manufactured by Bond Technologies, Inc. Elkhart, Indiana

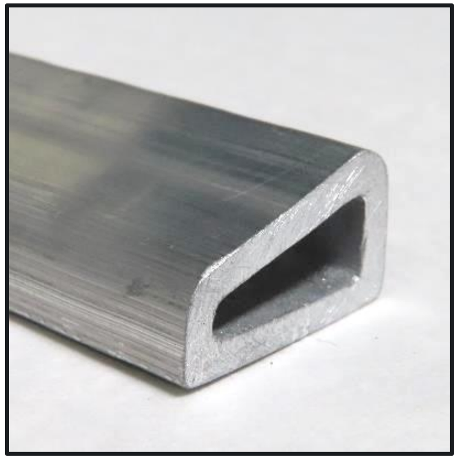
Demonstrated Product Applications

FSAM Feedstock
Ti Bar & Wire



High Conductivity
Cu & Al Wire

Hollow Multi-cell Profiles
1xxx, 6xxx & 7xxx Al Alloys



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Industry-Government Partnerships

Solid Phase PROCESSING

Aluminum Recycling

MAGNA

ATOMIC 13

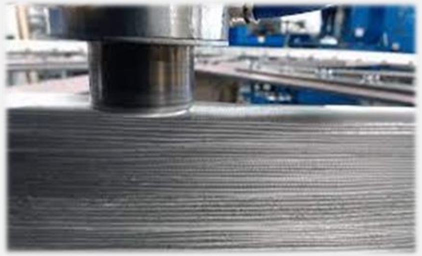
Cu & Al Conductors

EATON Powering Business Worldwide

Composites

SoCalGas

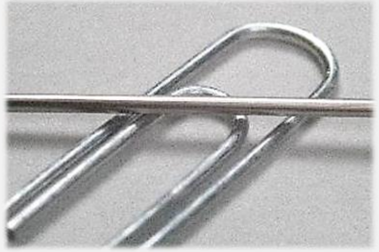
Additive Feedstock



BOEING

LOCKHEED MARTIN

Thermoelectrics



NNSA National Nuclear Security Administration

Exotic Alloys

ATI

Commercial Alloy Composition
Blending of 100% Post-Consumer Al Scrap

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Solid Phase PROCESSING

Twitch

Used Beverage Cans

6xxx & 3xxx RSI

Copper

	Si	Fe	Cu	Mg	Mn
Blend	0.72	0.43	0.23	0.74	0.43
6061	0.60	0.35	0.23	1.00	0.10

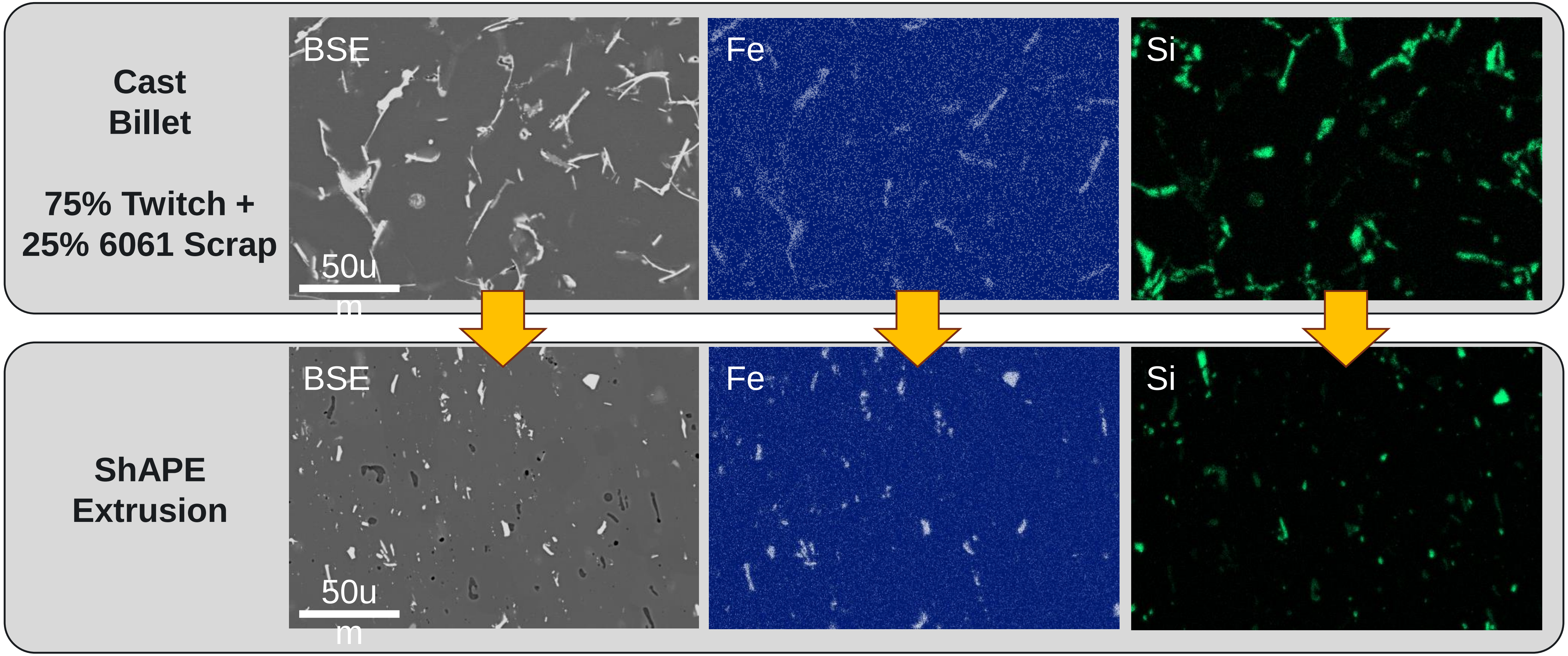
	Si	Fe	Cu	Mg	Mn
Blend	0.27	0.65	4.10	1.47	0.90
2024	0.25	0.25	4.35	1.50	0.60

	Si	Fe	Cu	Mg	Mn	Zn
Blend	0.58	0.28	1.62	2.39	0.10	5.55
7075	0.20	<0.25	1.60	2.45	0.15	5.65

“Similar” compositions relative to common alloys

Twitch Scrap

Recycling Post-Consumer Scrap



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Equivalent Material Properties

Recycling Post-Consumer Scrap vs Commercial Alloys

Solid Phase PROCESSING

Tensile properties validated by Westmoreland Testing & Research

WMT&R tm

Tensile Properties Measured Per ASTM B557-16

Alloy in T6	YS (MPa)	UTS (MPa)	Elongation (%)
100% Twitch	**288**	**363**	**10**
75% Twitch + 25% 6061	**262**	**356**	**16**
50% Twitch + 50% 6061	**270**	**342**	**14**

AA 6061 (ASTM-B221)	240	260	8
AA 6063 (ASTM-B221)	170	205	8

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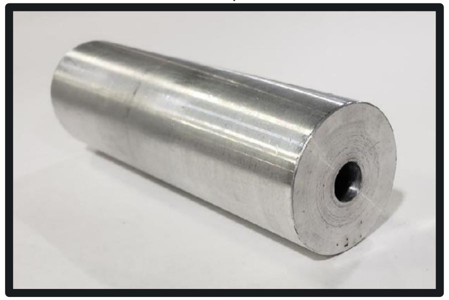
Aluminum 6063
High Fe Castings, Unhomogenized Secondary Scrap

Solid Phase PROCESSING

Extrude cast billets from 100% secondary scrap



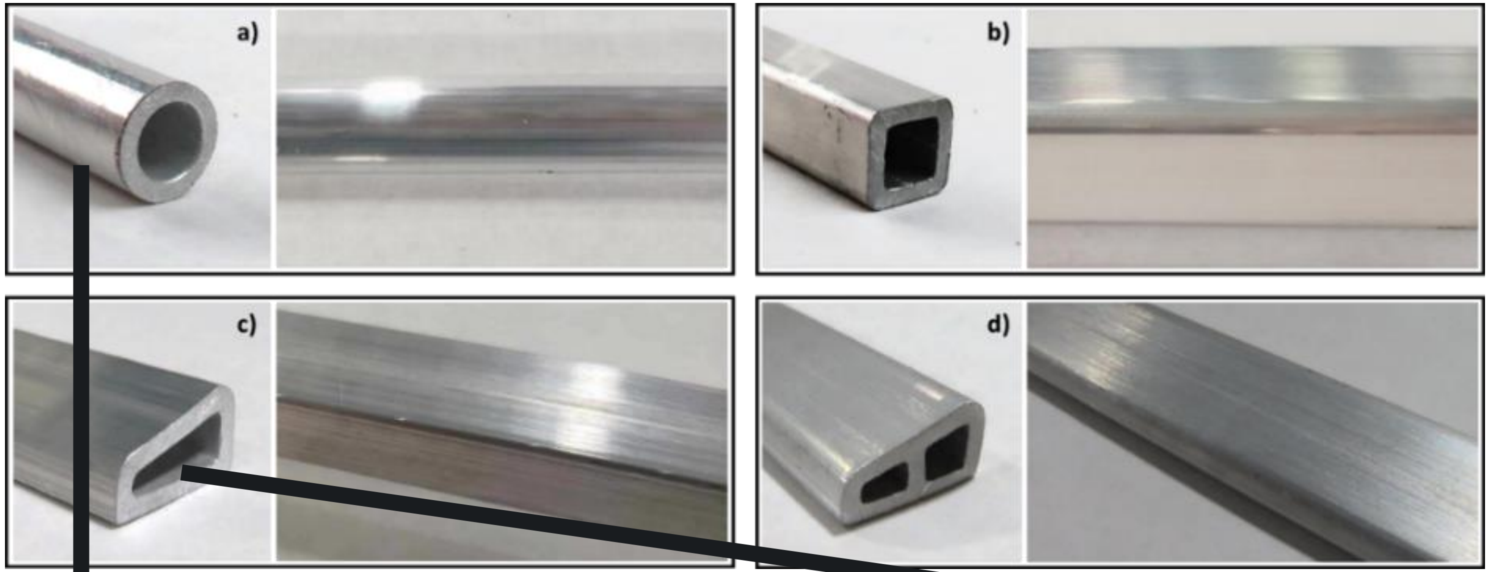
Al 6063	Fe
High Fe	0.34
Nominal Fe	0.21

6063-T6	YS (MPa)	UTS (MPa)	El. (%)
ASTM-B221	170	205	8
ShAPE .21% Fe	228	251	15
ShAPE .34% Fe	206	238	16

Whalen, S., N. Overman, B.S. Taysom, M. Bowden, Md. Reza-E-Rabby, T. Skszek, and M. DiCiano. In Review. "Effect of High Iron Content on Direct Recycling of Unhomogenized Aluminum 6063 by Shear Assisted Processing and Extrusion." *Journal of Manufacturing Processes*.

Aluminum 6063

Non-Circular Multi-Cell from Secondary Scrap



6063-T6	YS (MPa)	UTS (MPa)	El. (%)
ASM-B221	170	205	8
ShAPE of Unhomogenized Cast Billets	**247**	**271**	**17**

Demonstrated noncircular, asymmetric profile from 100% secondary scrap in 6063, 6061, and 6082

Whalen, S., B.S. Taysom, N. Overman, Md. Reza-E-Rabby, Y. Qiao, T. Richter, T. Skszek, and M. DiCiano. "Porthole Die Extrusion of Aluminum 6063 Industrial Scrap by Shear Assisted Processing and Extrusion." *Manufacturing Letters* (forthcoming).

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Opportunity for Sustainable Aluminum
Blending of Post-Consumer Scrap

Solid Phase PROCESSING

All new alloys, “similar” compositions to common alloys”

5% Wrought Twitch, 30% UBC, 65% 6xxx RSI, 0.3% Mg

	Si	Fe	Cu	Mg	Mn
Blend	0.60	0.40	0.18	0.95	0.38
6061	0.60	<0.35	0.23	1.00	0.10

99.4% 6xxx RSI, 0.6% Mg

	Si	Fe	Cu	Mg	Mn
Blend	0.64	0.31	0.13	0.70	0.11
6063	0.40	<0.20	0.05	0.67	0.05

20% Mixed Twitch, 26% UBC, 26% 3xxx RSI, 28% 6xxx RSI

	Si	Fe	Cu	Mg	Mn
Blend	1.26	0.55	0.44	0.84	0.51
6110	1.10	<0.40	0.45	0.80	0.45

67% UBC, 12.8% 3xxx RSI, 16% 6xxx RSI, 4.2% Cu

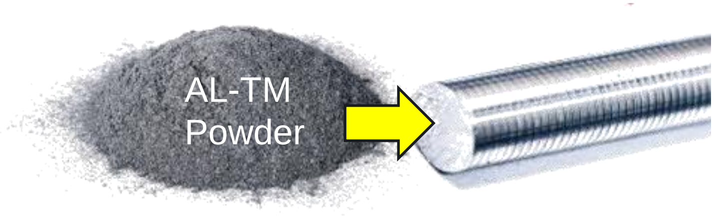
	Si	Fe	Cu	Mg	Mn
Blend	0.32	0.56	4.40	1.32	0.78
2024	0.25	<0.25	4.35	1.50	0.60

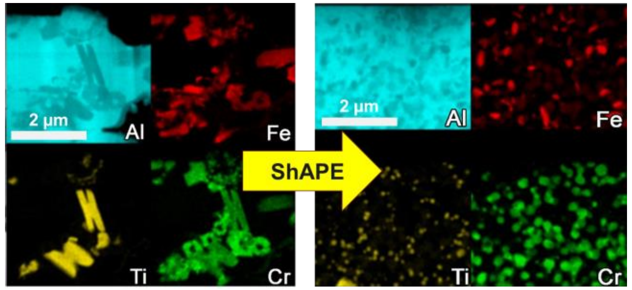
90.7% 6xxx RSI, 1.6% Cu, 2.3% Mg, 5.5% Zn

	Si	Fe	Cu	Mg	Mn	Zn
Blend	0.58	0.28	1.62	2.39	0.10	5.55
7075	0.20	<0.25	1.60	2.45	0.15	5.65

Peer Reviewed Publications
Pivotal Discoveries

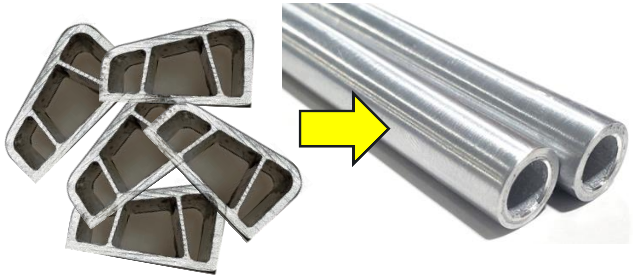
Refinement of 2nd Phase Intermetallics

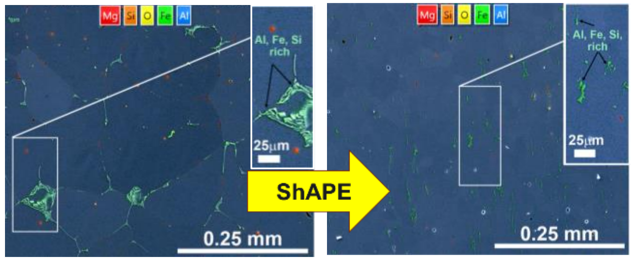




S. Whalen, M. Olszta, C. Roach, J. Darsell, D. Graff, Md. Reza-E-Rabby, T. Roosendaal, W. Daye, T. Pelletiers, S. Mathaudhu, N. Overman, "High Ductility Aluminum Alloy made from Powder by Friction Extrusion," Materialia, 6, 100260, 2019.

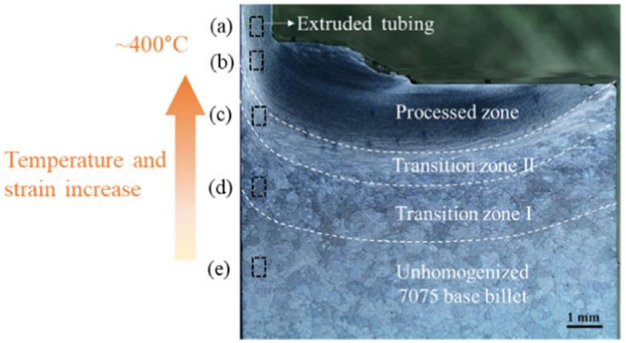
Refinement of AlFeSi in Scrap Al 6063

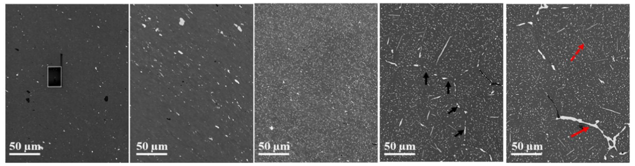




Whalen, S., N. Overman, B.S. Taysom, M. Bowden, Md. Reza-E-Rabby, T. Skszek, and M. DiCiano. In Review. "Effect of High Iron Content on Direct Recycling of Unhomogenized Aluminum 6063 by Shear Assisted Processing and Extrusion." *Journal of Manufacturing Processes*, vol. 97, pp. 115-124, 2023.

No Homogenization in Al 7075





T. Wang, J. Atehortua, M. Song, Md. Reza-E-Rabby, B.S. Taysom, J. Silverstein, T. Roosendaal, D. Herling, S. Whalen, "Extrusion of Unhomogenized Castings of 7075 Aluminum via ShAPE," Materials and Design, 213, 110374, 2022 (January).

ShAPE-enabled conversion of scrap-based extrusion feedstock

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PNNL is operated by Battelle for the U.S. Department of Energy
PNNL-SA-195930

Materials Recovery Technology for Defense Supply Resiliency

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Overview

- MRT-DSR
  - Mission: Five-pronged R&D Agenda
  - University-industry Collaborative Partners
  - Projects
- On-Demand Agile Manufacturing Using Forward Operating Base Metal Waste
  - The Need
  - Rapid Casting from Waste Metals
  - Design of a Mobile Foundry
- Looking Forward

Mission: Five-pronged R&D Agenda

Mission

- Basic research to determine whether critical and strategic metals and materials can be "harvested" from recovered and/or recycled sources.
- Projects done in collaboration with the US Department of Defense, Academia and Industry
- Multi-year R&D initiative

Agenda

- Advanced technological recovery of defense critical & strategic materials
- Plastics and polymeric materials recycling
- Advancement of additive manufacturing for defense applications
- Development of on-site tech for reclamation of basic metals and e-waste
- Energy materials reclamation & recycling

University Industry Collaborative

30 Projects

- Applied Materials
- Gas Technology Institute
- Indium Corp.
- GDB Intl.
- Grensol
- Terves
- ErCo

- WPI
- Univ. of Toronto
- Purdue University
- Univ. of Maryland
- Univ. of Minnesota
- KU Leuven, Belgium
- Univ. of Queensland

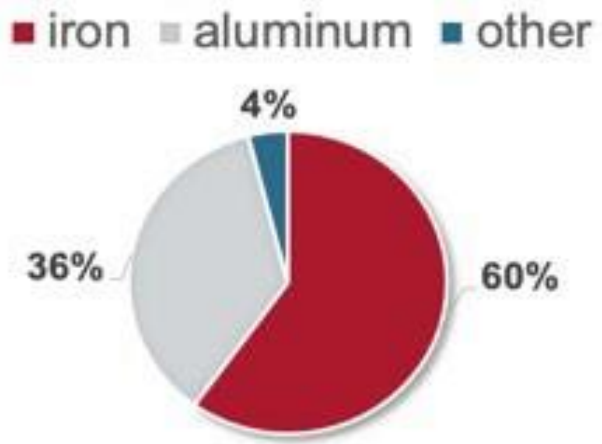
Example Projects

- **Recycling of Non-metallic components in Automotive Lithium-ion Batteries**
- **End-to-end Recycling and Components Recovery and Reuse in a Lead Acid Battery**
- **Recovery of Terbium and Europium from Spent CFL Lights**
- **Value-added Products Recovery from Bauxite Residue Waste**
- **In-situ Smelting of Discarded Urban Scrap into Aluminum Alloys**
- **On-Demand Rapid Fabrication of Components Using Forward Operating Base Metal Waste**

On-Demand Agile Manufacturing Using Forward Operating Base Metal Waste

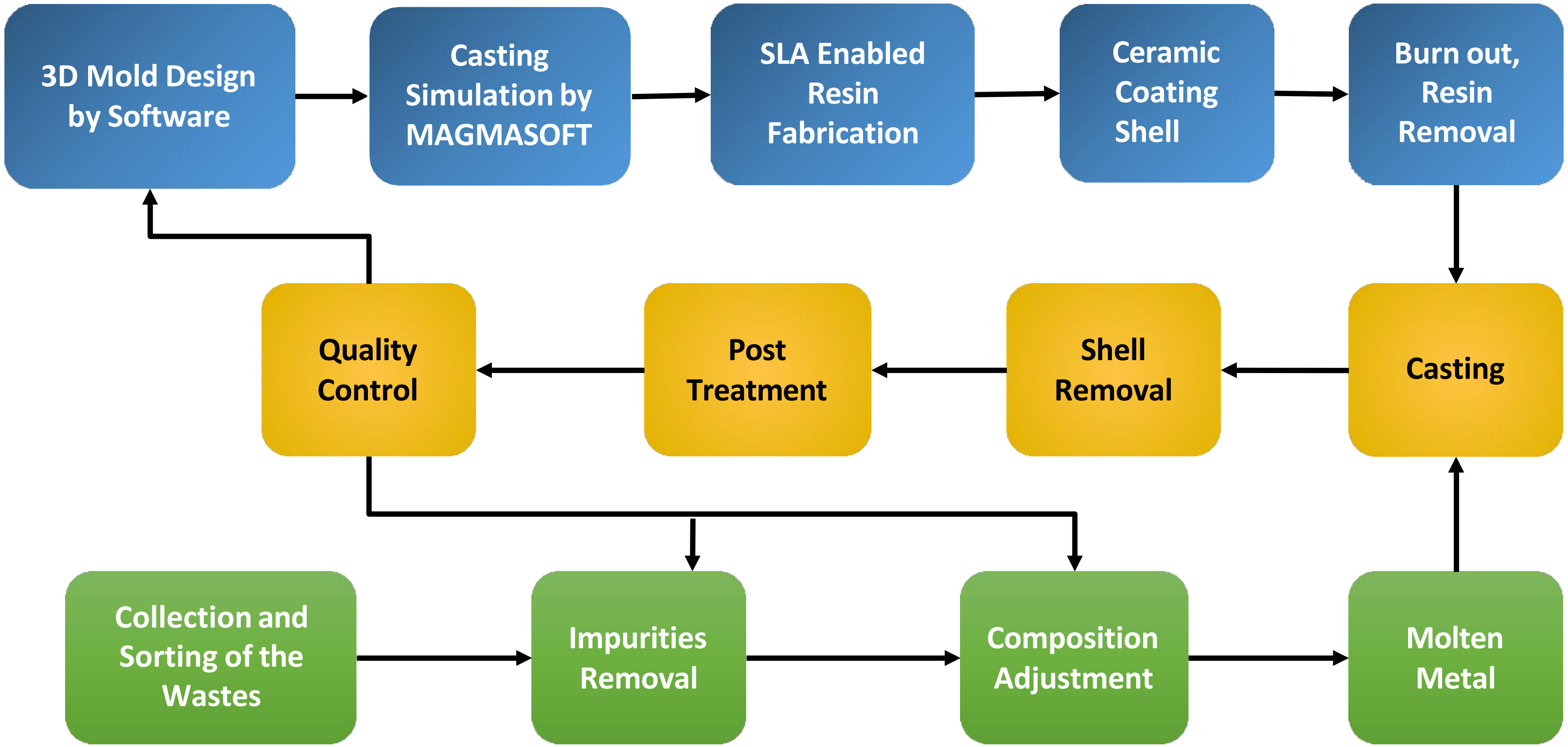
Overview

- Ferrous (iron) and aluminum waste make up the largest category of metals in solid waste at Forward Operating Bases (FOBs)
- Currently, the disposal of solid waste is very dependent on the duration of a campsite, the current security situation of a particular site, and the ability and willingness of local infrastructure to handle these wastes
- Need to develop a manufacturing process and enable the fabrication of replacement parts or repair operation in the field



Recommended breakdown of metal waste recipe at FOBs

Waste Material to New Parts




(a)


(b)

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Expeditionary Lab (Ex Lab)

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Waste Material Sorting

- 2,567.00 lb. of Waste Metal Received from ARL.
- Portable OES (Hitachi High-Tech PMI Master UV Touch)
- Established a waste metal database.

Picture of Scrap	Categorization	Dimensions (Approximate, Overall Size)	Contamination	Weight (lbs.)	Grade	Fe(%)	C(%)	Si(%)	Mn(%)	Cr(%)	Mo(%)	Ni(%)	Al(%)	Co(%)	Cu(%)
	Hydraulic	27"x10"	Coating, Partial, Plastic Comp, Hydraulic Fuel	14.14	1005-AISI	99.5	0.0551	0.012	0.188	0.0398	<0.003	<0.005	0.0357	0.002	0.0201
	Exhaust Pipe	22"x6"	Partial Rust	6.49	1005-AISI	99.5	0.0616	<0.005	0.273	/	<0.005	<0.005	0.0294	0.0061	0.03
	Tank	20"x10"x6"	Partial Rust, Coating, Plastic Comp.	6.17	1005-AISI	99.2	0.0887	0.0117	0.513	0.0378	<0.003	0.0119	0.0373	0.0029	0.0357
	Conduit Box	18.75"x13.5"x4.75"	Coating, Partial Rust, Internal Components	15.47	1005-AISI	99.6	0.0619	<0.005	0.178	0.0122	<0.003	0.0069	0.0186	0.0041	0.0112
	50 Gallon Drum Lid	23.5"x1"	Entirely Covered in Rust	6.18	1005-AISI	99.5	0.0698	0.0095	0.224	0.0326	0.0032	0.0073	0.0414	0.0027	0.0441
	Hollow Square Tube	8x4 1/8x8 3/8	Partial Rust	6.03	1005-AISI	98.7	0.248	0.0064	0.818	0.0136	<0.003	<0.005	0.042	0.0035	0.0181

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Selecting Waste Pieces to Formulate New Alloy

Steel 1 Carbon Steel

		CE	DI	% C	% Si	% Mn	% P	% S	% Cr	% Mo	% Ni	%Al	%Co	%Cu	%V	%Sn
Recovery				0.9	0.95	0.95	1.0	1.0	0.97	0.99	0.99	1.0	1.0	1.0	1.0	1.0
Target	Min.	0.23	0.27	0.15	0.40	0.50	0	0	0	0	0	/	/	/	/	/
	Max.	0.67	4.25	0.30	0.60	1.20	0.035	0.035	0.50	0.20	0.50	/	/	/	/	/
Heat Composition		0.35	0.69	0.147	0.506	0.768	0.021	0.013	0.190	0.054	0.343	0.015	0.005	0.180	0.009	0.011
Heat Size (lb.)	70															

Waste Parts	Name	Remain	Added (lb.)	Fraction	Dimensions	% C	% Si	% Mn	% P	% S	% Cr	% Mo	% Ni	%Al	%Co	%Cu	%V	%Sn
#3-35	Plate with Square Hole	45.400	54.600	0.780	27.75" x 15.125" x 1.0"	0.136	0.050	0.809	0.017	0.008	0.077	0.014	0.084	0.019	0.003	0.188	0.001	0.009
#4-15	Big Thread Barrel 5	32.780	10.000	0.143	4.5" x 24"	0.355	0.320	0.739	0.055	0.022	0.879	0.284	1.870	0.002	0.017	0.090	0.052	0.020
#3-32	Big L Beam	27.810	5.000	0.071	3.0" x 3.0" x 64.0"	0.087	0.270	0.972	0.002	0.048	0.123	0.037	0.189	0.001	0.009	0.284	0.022	0.015

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Direct Fabrication of IC Patterns by SLA

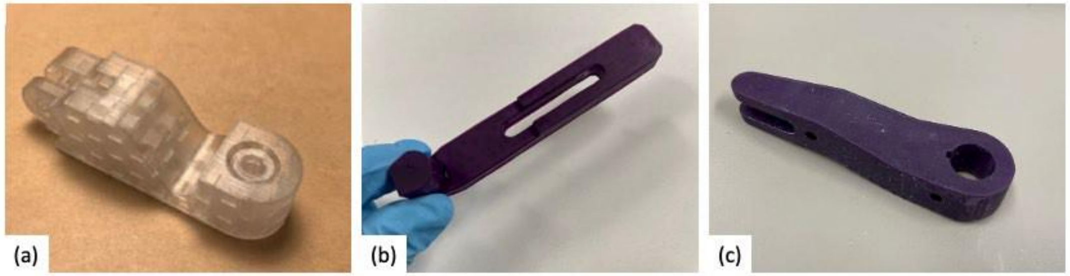
3D System
ProJet 6000 HD

FormLabs
Form 2

3D SYSTEMS

formlabs

Model (Brand)	ProJet 6000 HD (3D System)	Form 2 (FormLabs)
Dimensions (mm)	787*737*1829	350*350*520
Weight (kg)	181	13
Min. Layer Thickness (mm)	0.05	0.03
XY Accuracy (mm)	0.025	0.14
Max. Biuld Size (mm)	250*250*250	146*145*175
Price ($)	185,000	3,499



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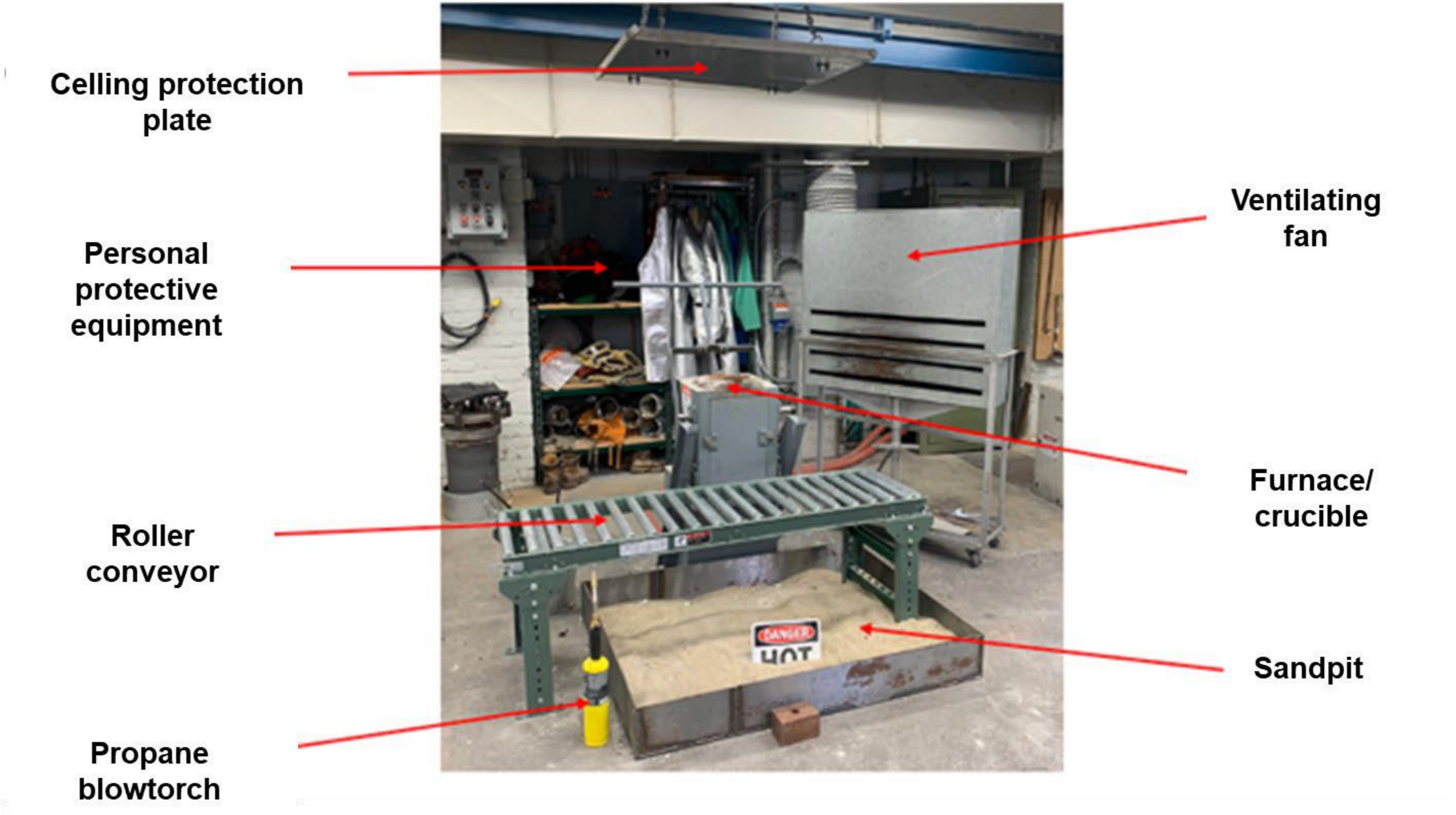
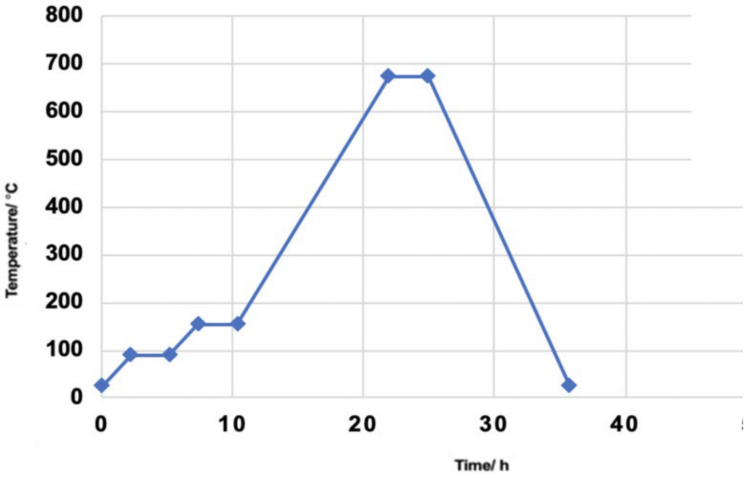
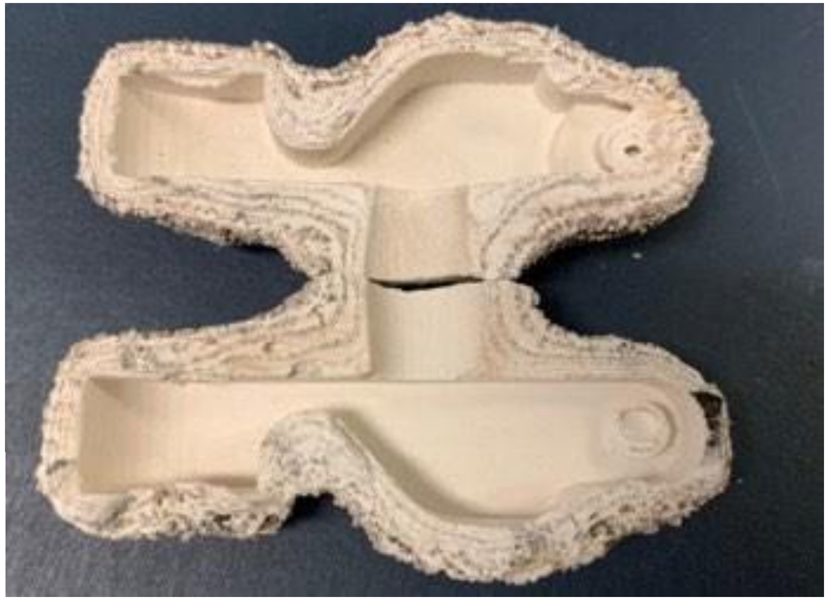
Compact Steel Casting System

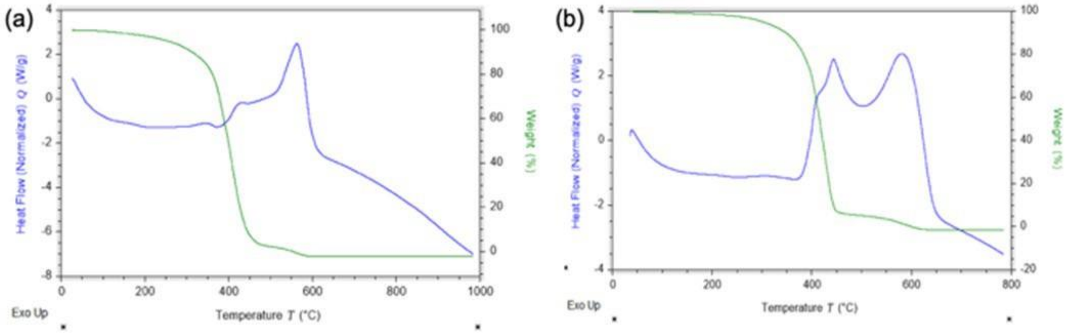


Ceramic Shell Making and Burnout

Layer	Slurry	Stucco Material
1	Primary	Zircon Sand
2	Primary	Zircon Sand
3	Primary	Mulgrain 47 60S
4	Primary	Mulgrain 47 60S
5	Primary	Mulgrain 47 22S
6	Primary	Mulgrain 47 22S



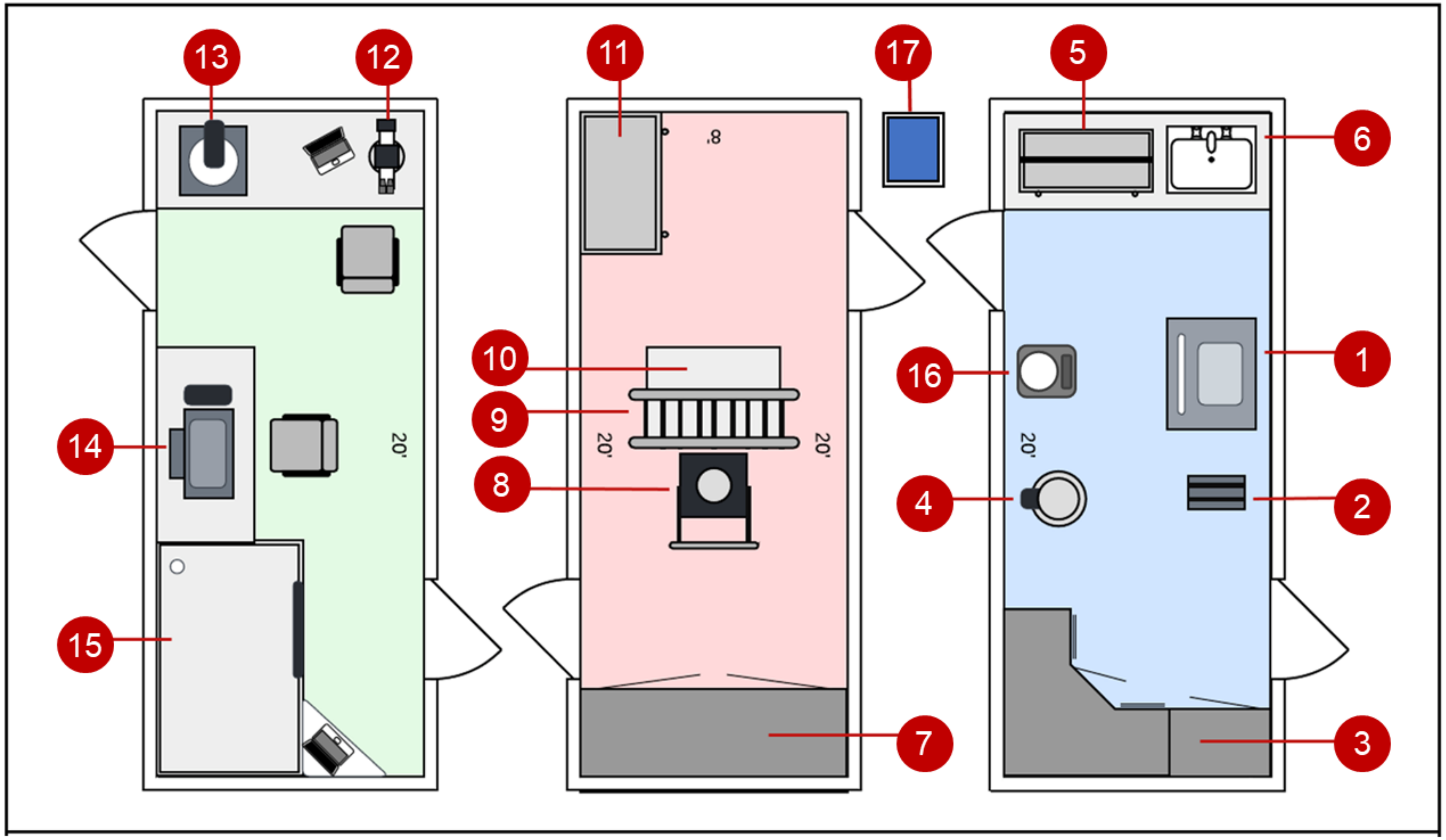




Casting

Time (Minutes)	Power (kW)	Action
0	0	Add waste material into crucible
0-30	17	Crucible preheat
30-90	30	Main melting stage
90-110	25	Conduct composition analysis, adjust composition
110-140	30	Temperature measuring, pouring

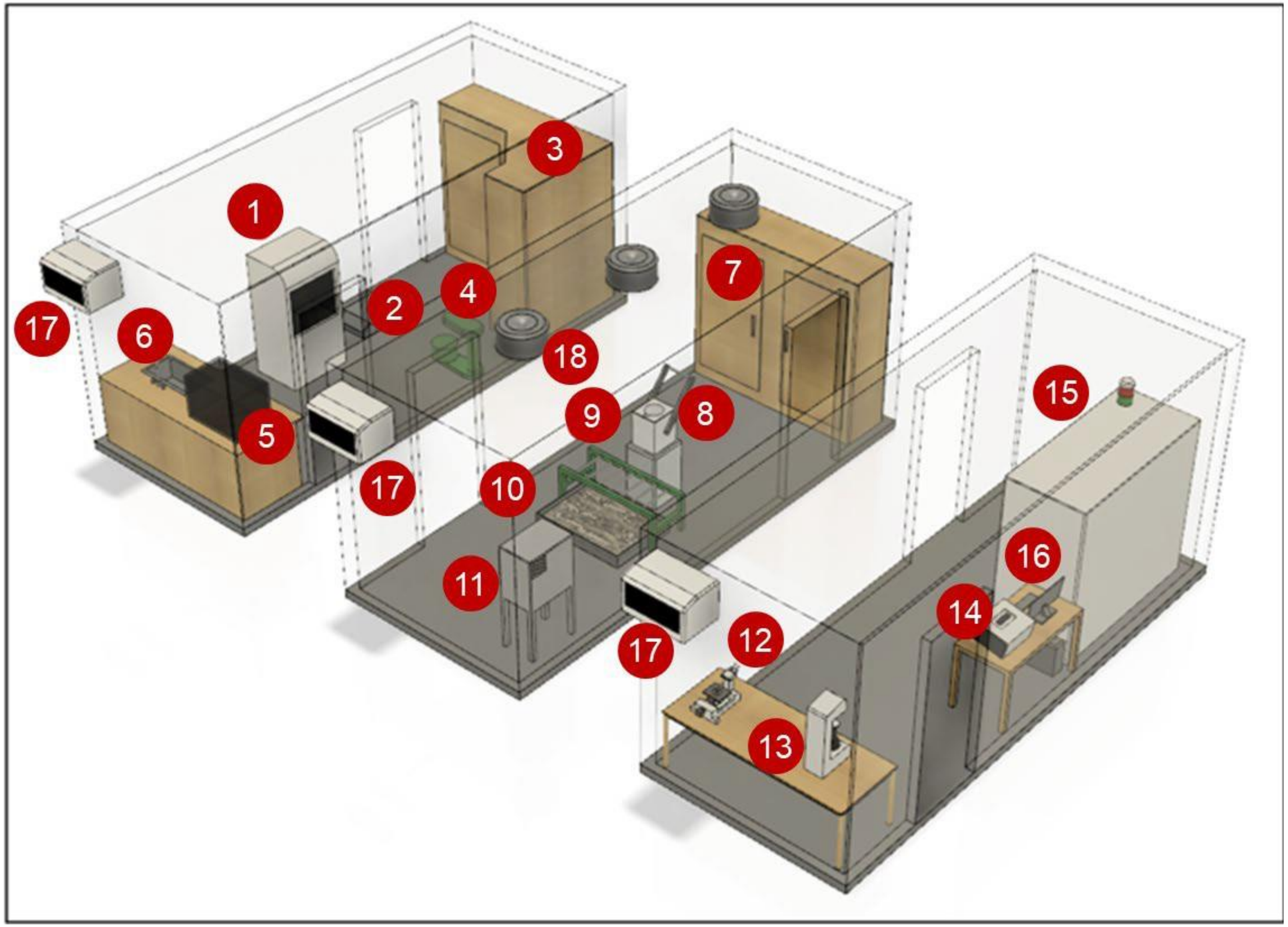
Mobile Foundry Design



Investment Preparation Area
Casting Area (Hazard Area)
Product Characterization Area

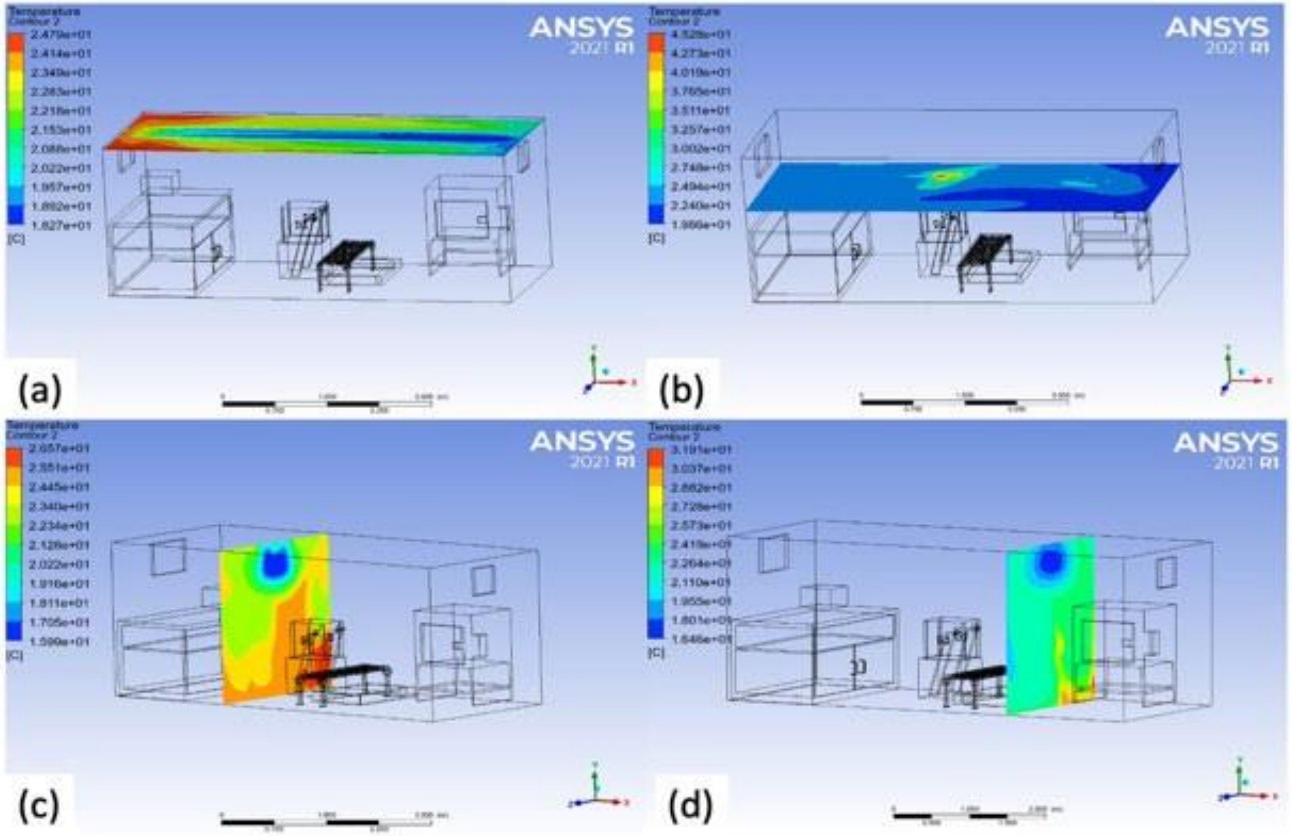
1. 3D Printer 2. Jar Mill 3. Storage 4. Sand Mixer 5. Drying Box
6.Sink 7. PPE Closet 8. Steel furnace 9. Conveyor 10. Sand pit
11. Box Furnace 12. Microscopy 13. Hardness Tester
14.Portable OES 15. CT 16. Balance 17. Quenching Tank

Mobile Foundry Design



1. 3D Printer
2. Jar mill
3. Storage
4. Sand mixer
5. Drying box
6. Sink
7. PPE Closet
8. MiniMetl
9. Conveyor
10. Sand pit
11. Box furnace
12. Microscopy
13. HRC tester
14. OES
15. CT
16. Computer
17. ACs
18. Ventilations

Safe Operation



Scenario 1:
Crucible covered with insulation blanket, 456.45 °C max temperature. The A/C is intaking 500 CFM of 16°C air while the exhaust fan is exhausting 500 CFM of air

Scenario 2:
Crucible top open to air, 1682.22°C max temperature. The A/C is intaking 700 CFM of 13.9°C air while the exhaust fan is exhausting 700 CFM of air

(A/C intaking 500 CFM of 16^{0}C air while the exhaust fan was exhausting 500 CFM of air). (a) Section view on xz plane at ceiling, (b) section view on xz plane at head height, (c) section view on yz plane behind the induction furnace, (d)section view on yz plane in front of induction furnace. ***Note****: CFM = cubic feet per minute*

Microgrid Power System

- Pre-wired microgrid solution with integrated solar array, battery storage, intelligent inverters, optional backup generator
- Can cover typical power demand of 45kW of the mobile foundry system by a microgrid system in 20-foot shipping container

BoxPower SolarContainer:

- Scalable and replicable
- Off-grid and grid-tied functionality
- Easy installation
- Minimal foundation requirements
- Pre-wired outlets for plug-and-play
- Effectiveness in extreme weather conditions
- Permit-ready for permanent or temporary use
- Fully automated with remote monitoring and control

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Technology Transfer-Instruments

Name	Company	Type	Weblink	Power	Size	Note
3D printer	Formlabs	Form 2	Form 2	100-240 V, 1.5A,60Hz, 65 W	18*18*27 (inch)	Max print size: 145 × 145 × 175 mm
Jar mill	MSE supplies	MSE PRO	MSE PRO	110V(AC), 50/60Hz, 750W	29*16*10 (inch)	Max. Loading Capacity: 35 kg
Sand Mixer	Avantco	MX20	MX20	120 V, 60Hz, 1100 W	17*28*37 (inch)	High RPM of 485
Box furnace	Mellen	MV microtherm	MV microtherm	208/240V, 5400W	9*9*14 (inch)	Operates T:up to 1250ºC in air
ACs	Friedrich	KCM21A30A	KCM21A30A	230 V, 15A, 60Hz, 2092 W	29* 26*18 (inch)	Cooling power: 21500 BTU
Ventilation	Global industry	T9F294497A	T9F294497A	110 V 50W	27*27*8.5 (inch)	Fan diameter: 24 inch
Induction furnace	Inducto-therm	Mini melt		460V(3P), 9600 Hz, 15-35 kW	32*25*53 (inch)	
Micro-scopy	New York Microscope	ACCU-SCOPE 3000	ACCU-SCOPE 3000	110/240V	15*7.7*15.4 (inch)	400X Magnification
HRC tester	Govets	Bench top Hardness tester	Bench top Hardness tester	N/A	5*9.4*24.8 (inch)	Scale type: Rockwell
OES	Hitachi	PMI-MASTER Smart	PMI-MASTER Smart	28.8V(DC) 25/500 W	9.3*16.1*16.7 (inch)	spark modes: 300
CT	Nikon	XT H225	XT H225	20-450 W	72*33.6*78 (inch)	X-ray solution: 225 kV

MRT-DSR Team We are.....

Highly skilled researchers contributing to the revitalization of the manufacturing base

supplying know-how to DoD-specific needs

that can be adopted by industry to delivery tomorrow's advanced metals recovery technology.

Thank You!

Data-driven design from Rubble 2 Rockets

Miguel A. Bessa (miguel_bessa@brown.edu)
Associate Professor
School of Engineering, Solid Mechanics Group
Brown University

March 18, 2024

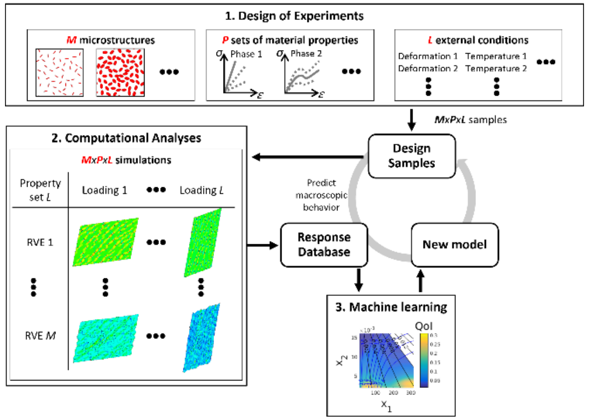
DARPA R2 Industry Day | Lightning Talk

Method development and application of machine learning to design materials and structures

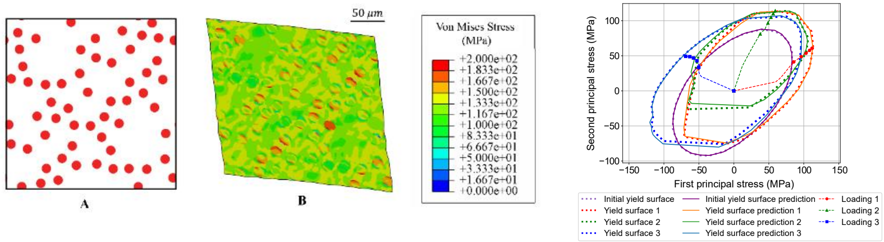
Method development

- Open-source framework for Data-driven Design & Analysis of Structures & Materials
- Recurrent Neural Networks to learn history-dependent constitutive modeling (e.g. plasticity)

Computer Methods in Applied Mechanics and Engineering (2017), 306, 319-341.



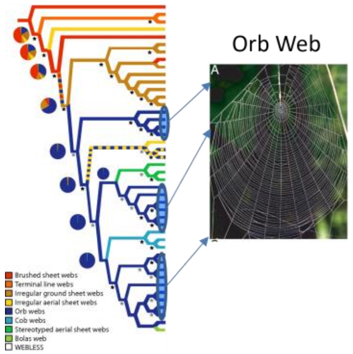
Proceedings of the National Academy of Sciences (2019), 116(52), 26414-26420.



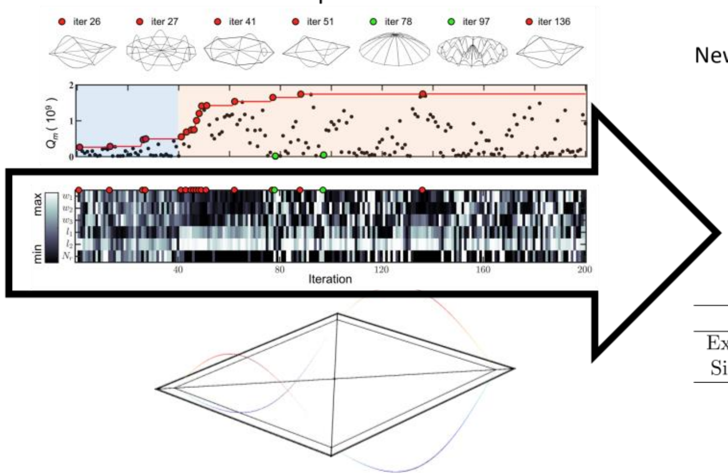
Application

- Machine learning guided design of reversible super-compressible mechanical metamaterial
- Machine learning guided design of spiderweb nanomechanical resonator

Millions of years of evolution

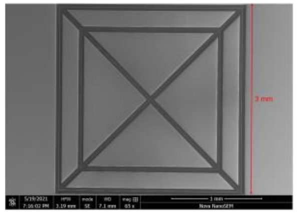


Machine learning guided optimization with microchip material

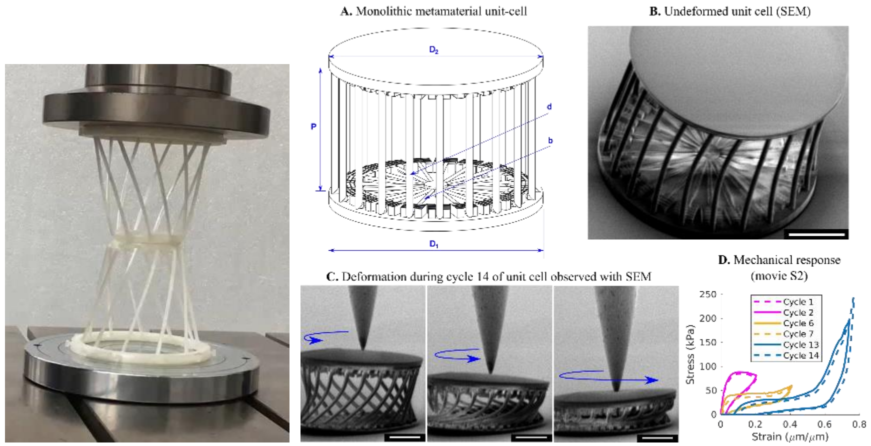


Found new mode leading to best performance to date!

New sensor using high-stress SiN



	Q_m	f_m
Experiment	1.82×10^9	133.5 kHz
Simulation	1.75×10^9	134.9 kHz



Advanced Materials (2019), 31(48), 1904845

Advanced Materials (2022), Front Cover, 34(3), 210624

Video Disabled

Video can be provided upon request.

Avoiding Lock-In: Change Propagation Analysis and Design for Flexibility

Professor Olivier L. de Weck
Massachusetts Institute of Technology
Editor-in-Chief *Journal of Spacecraft and Rockets*

DARPA Rubble to Rockets (R^2) Industry Day

18 March 2024

What is “Lock-In” ?

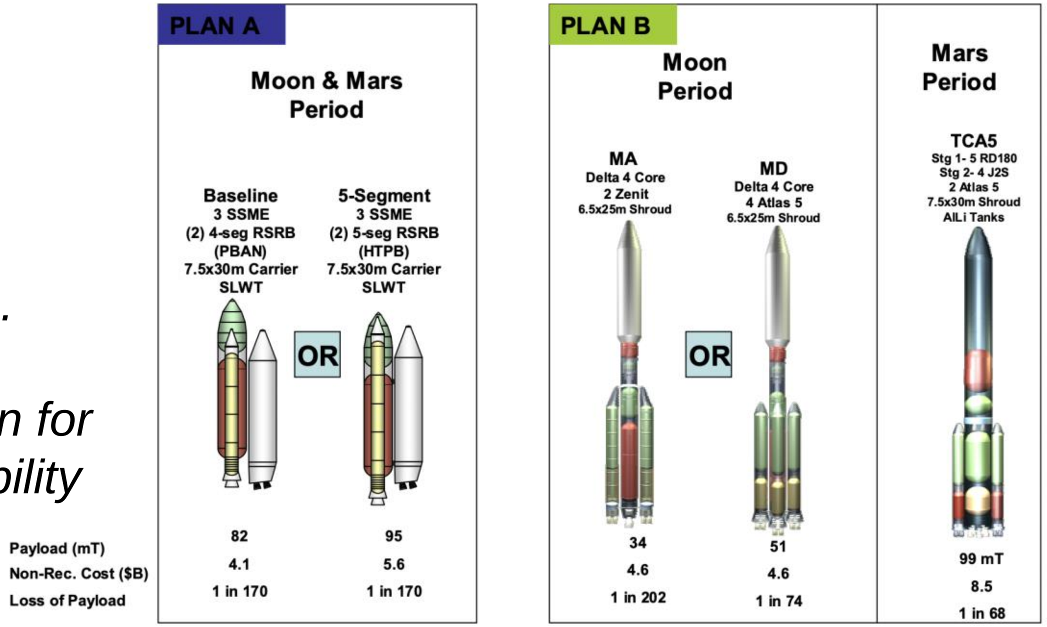
“Lock-In” is the inability to make changes to a design even though we would like to, because it is perceived as being too expensive or would take too much time.

Example: SLS

$2B/launch

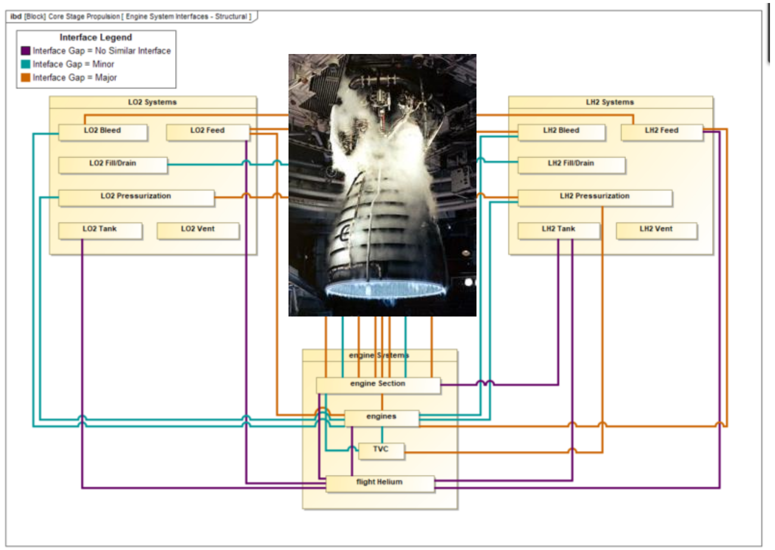
vs.

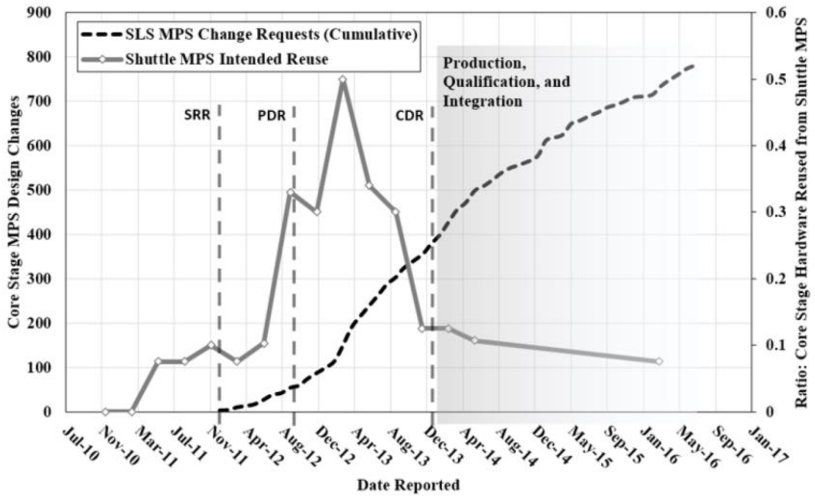
Design for Flexibility

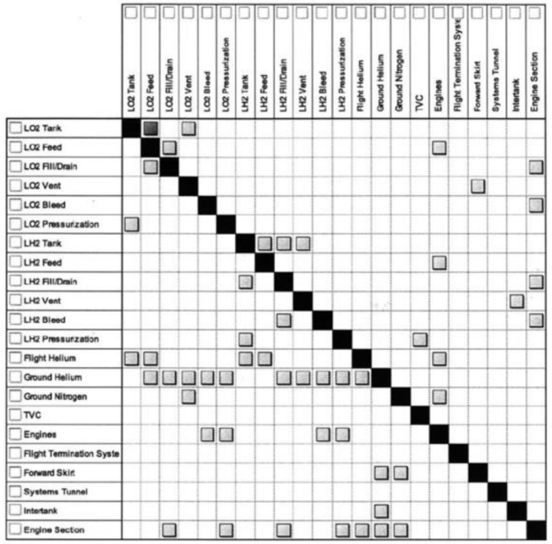


Silver, Matthew R., and Olivier L. de Weck. "Time-expanded decision networks: A framework for designing evolvable complex systems." *Systems Engineering* 10, no. 2 (2007): 167-188.

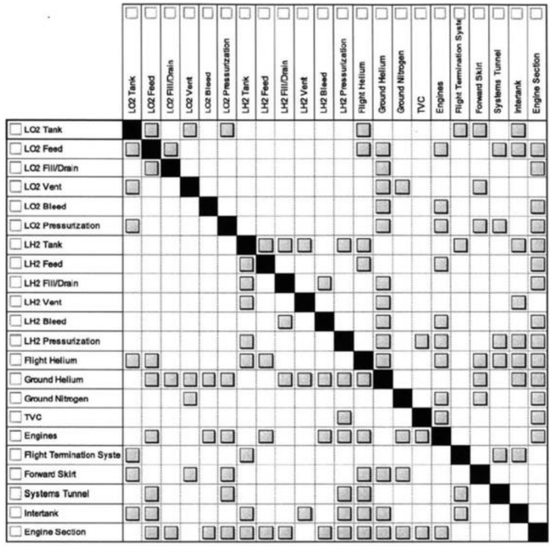
SLS Core Stage: RS-25 Mandated Reuse







(a)
Flow DSM (Directed)



(b)
Structural DSM (Not directed)

*Estimated a Cost Multiplier ratio for "with-reuse" vs. "from-scratch" in Table 5.11 (that is, 4.124=1.819 = **2.27**)*

Trujillo, Alejandro Elio. "A Model-based Methodology for Strategic Reuse of Legacy Designs in Space Mission Architecting." PhD diss., Massachusetts Institute of Technology, 2021.

Change Propagation Analysis

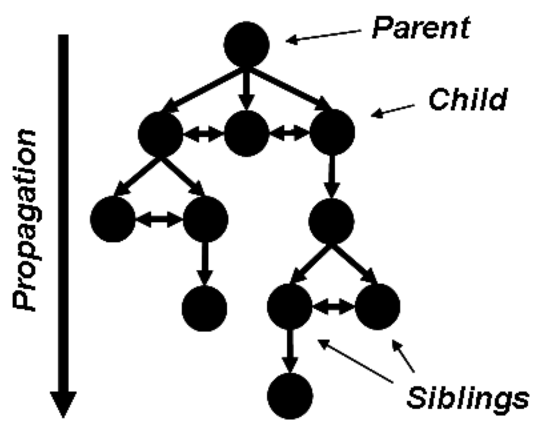
- Changes are inevitable during design

- Changes are
  - **Good**: improve products, satisfy customers, help us better compete in the market
  - **Bad**: consume time, money, and resources

- Change propagation
  - One change triggers another change
  - Adds to the final cost of the intended change

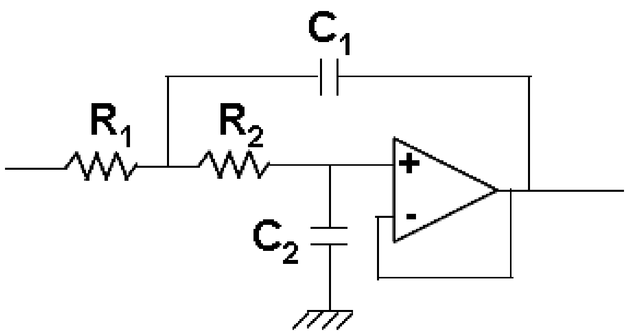
- Design for flexibility (“adaptive design”)
  - Think about potential future changes in design in advance to minimize change propagation
  - Lower the ”switching cost” upfront

Change Propagation



Hypothetical Example (1 of 2)

Sallen-Key Low-Pass Filter



Product Components

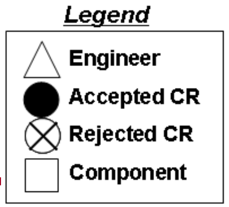
- Performance requirements
  - Cutoff frequency, ω_C
  - Quality factor, Q
- Design variables
  - Resistors, R_1 and R_2
  - Capacitors, C_1 and C_2

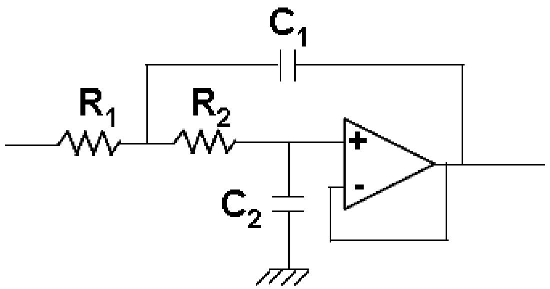
Performance Equations

$$\omega_c = \frac{1}{2\pi\sqrt{R_1 R_2 C_1 C_2}}$$

$$Q = \frac{\sqrt{R_1 R_2 C_1 C_2}}{C_2 (R_1 + R_2)}$$

Hypothetical Example (2 of 2)

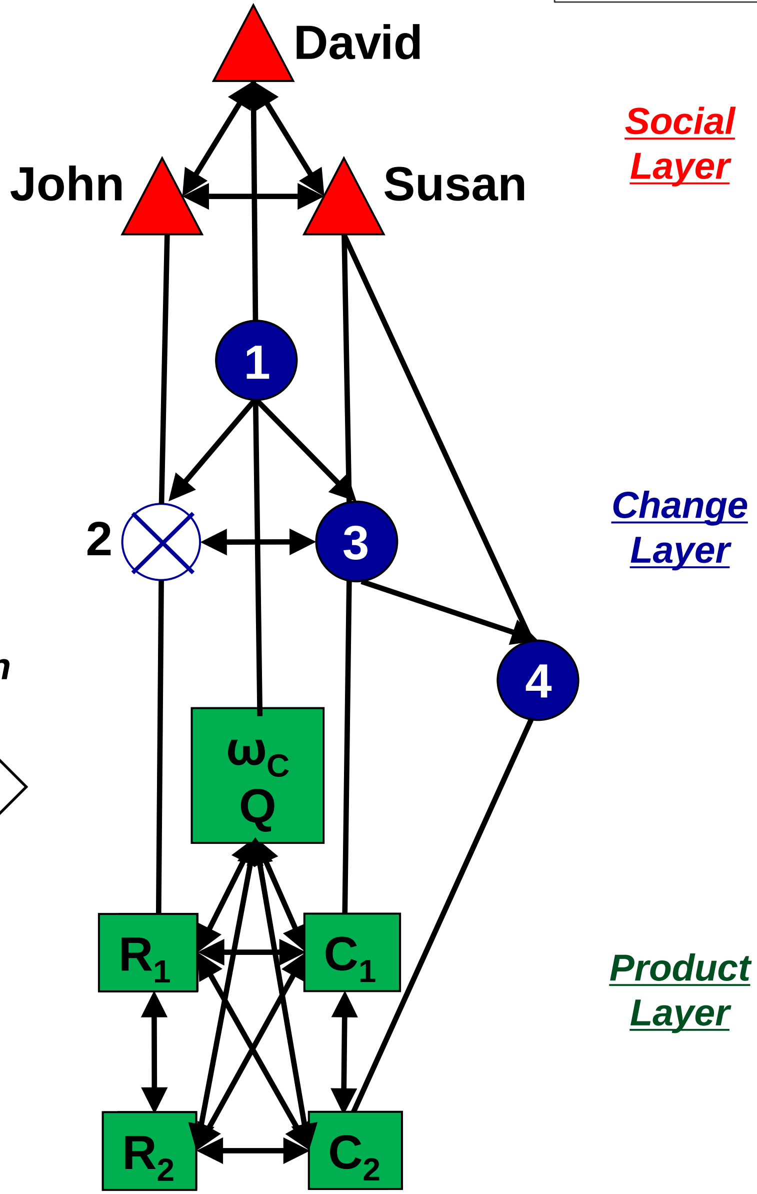




Change Activity

- Change #1
  - David changes performance requirement ω_C
- Change #2
  - John plans to change resistor R_1, but this change is rejected
- Change #3
  - Susan changes capacitor C_1
- Change #4
  - Susan changes capacitor C_2

Model Construction



Quantifying Design Change Behavior

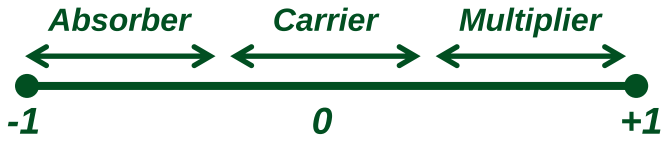
Component Behavior

Propagation DSM

Instigating Component (columns) / Affected Component (rows)

	ω_C/Q	R_1	R_2	C_1	C_2
ω_C/Q					
R_1					
R_2					
C_1	1				
C_2				1	

Change Propagation Index (CPI)



$$CPI = \frac{C_{out} - C_{in}}{C_{out} + C_{in}}$$

C_{in} = *in degree*

C_{out} = *out degree*

ω_c: multiplier (CPI = +1)

C_1: carrier (CPI = 0)

C_2: absorber (CPI = -1)

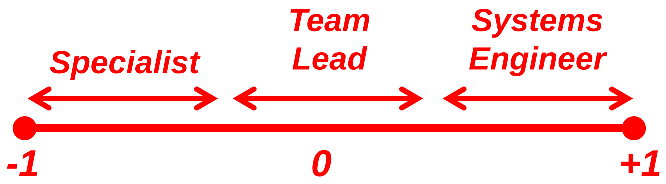
Engineer Behavior

Propagation DSM

Instigating Engineer (columns) / Affected Engineer (rows)

	John	Susan	David
John			
Susan		1	1
David			

Engineer CPI



$$CPI = \frac{E_{out} - E_{in}}{E_{out} + E_{in}}$$

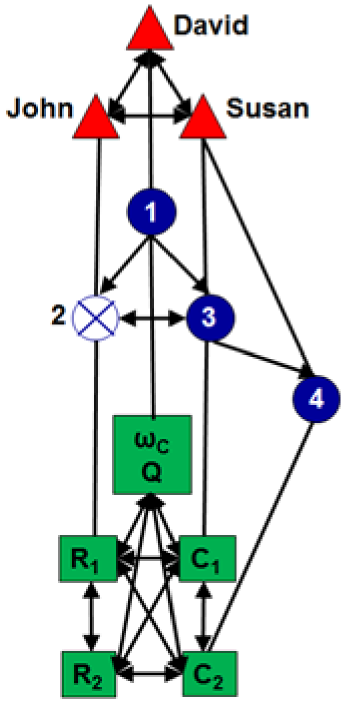
E_{in} = *in degree*

E_{out} = *out degree*

David: sys. eng. (CPI = +1)

Susan: specialist (CPI = -0.3)

Hypothetical Application

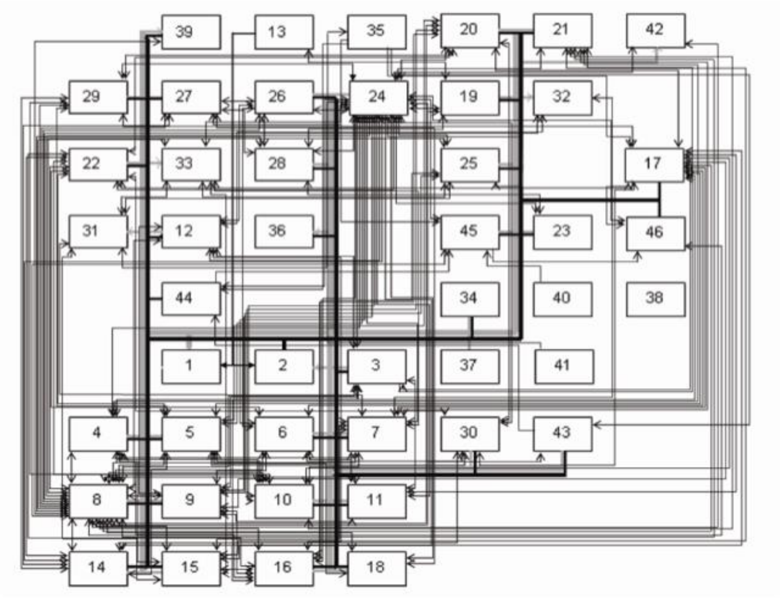


Pasqual, Michael C., and Olivier L. de Weck. "Multilayer network model for analysis and management of change propagation." *Research in Engineering Design* 23 (2012): 305-328.

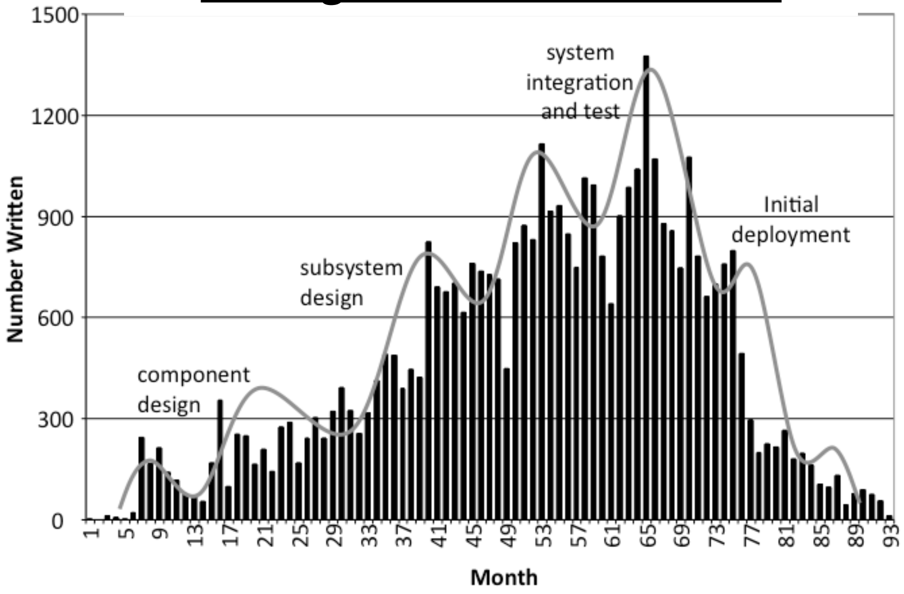
BX-1 SPOTD, The World’s Largest X-Band Radar

Change Propagation at Scale

System Diagram*



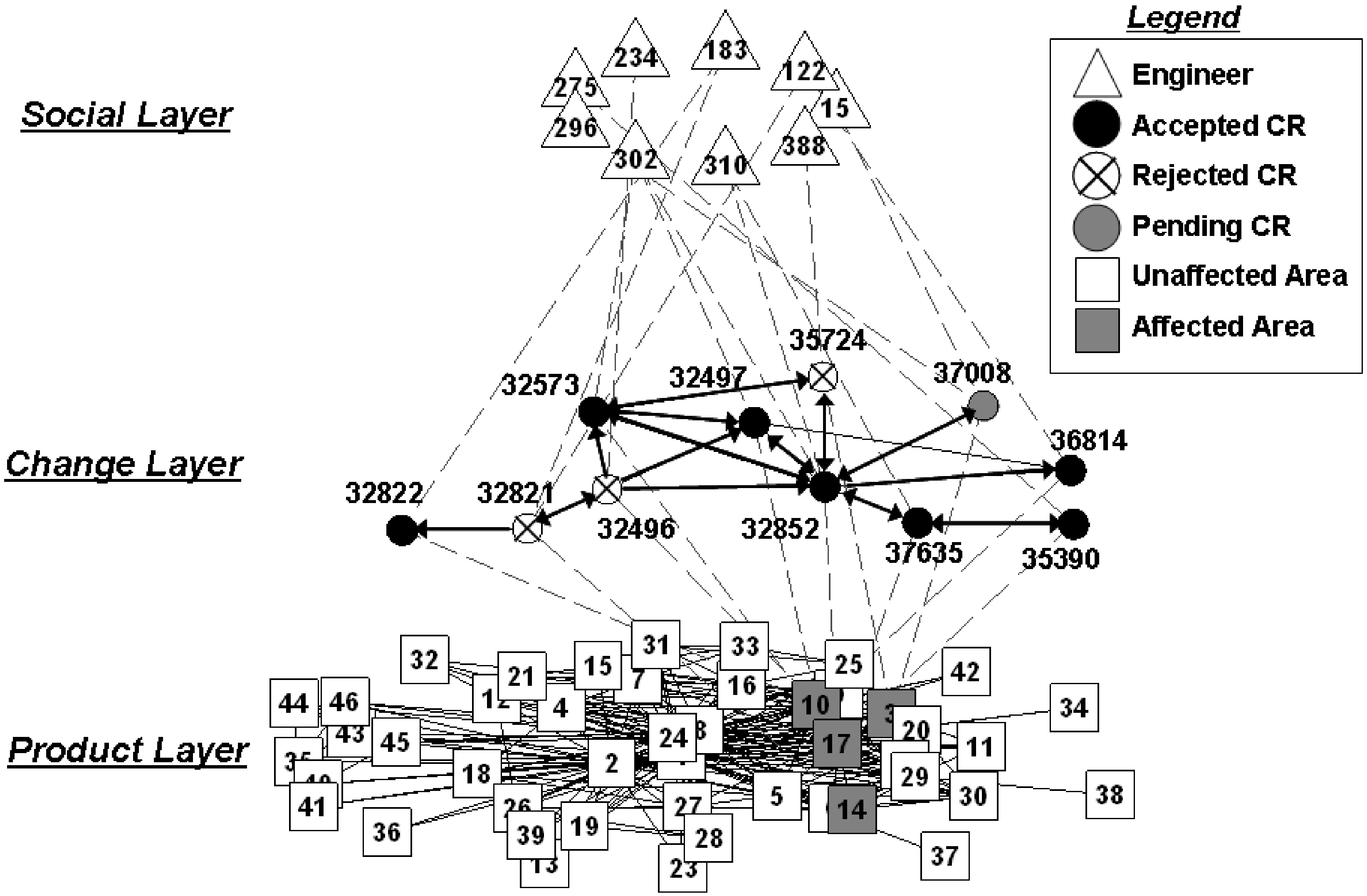
Change Volume Timeline*



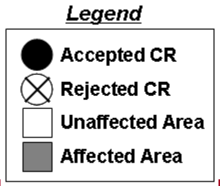
- Large-scale sensor system
  - Globally distributed hardware and software
- 8-year development program

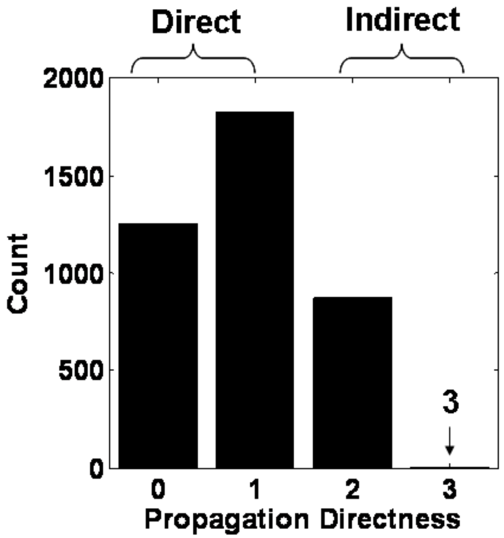
* Giffin et al. (2009) Change propagation analysis in complex technical systems. Journal of Mechanical Design: 131 (8)

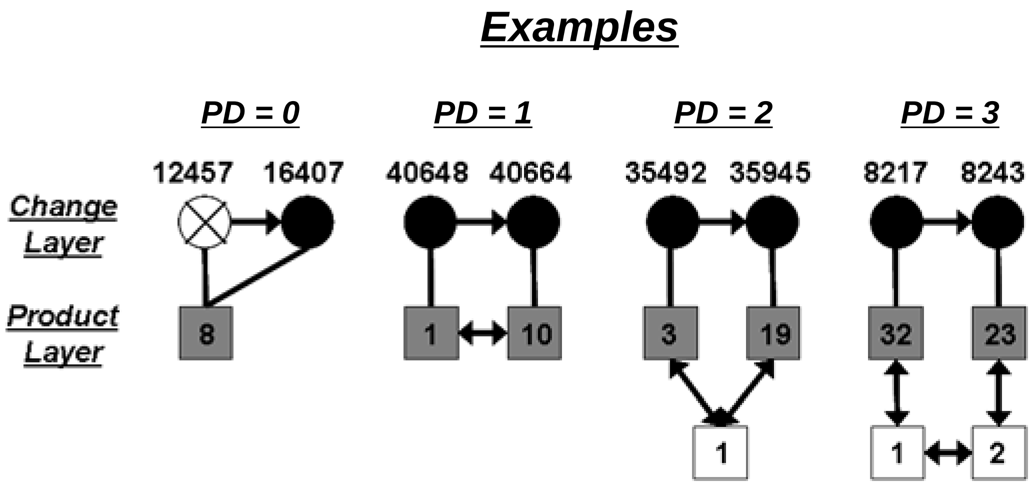
Example Design Change Network



Propagation Directness (PD)







- Propagation Directness (PD) is the # of interfaces between an instigating component and an affected component

- Two types of propagation:
  - Direct (PD ≤ 1): components affect adjacent components
  - Indirect (PD ≥ 2): components affect non-adjacent components
    - ~ Counterintuitive phenomenon
    - ~ Feature of software systems

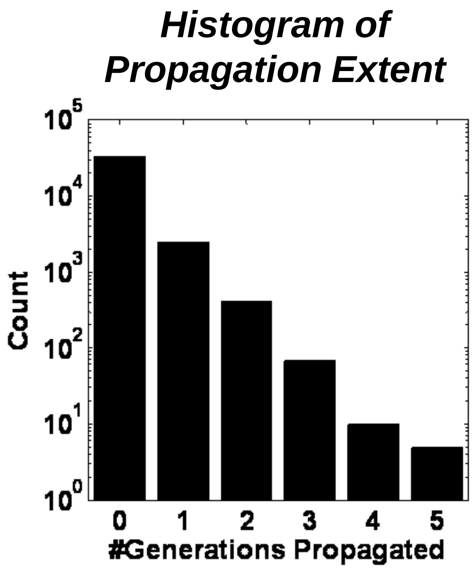
Will DARPA R^2 have to deal with indirect changes since it is mainly structural?

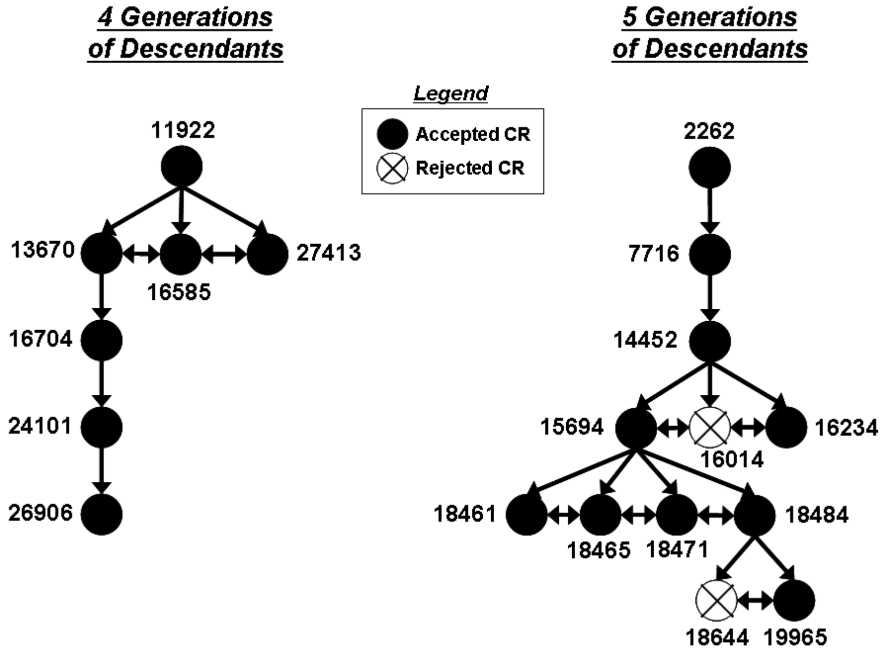
R^2 Example: Sounding Rocket Design

Hypothetical Change Propagation Scenario (R^2 inspired)

N_2O tank material → *Stainless Steel 409* → *1* (*switch material*) → *Scrap Cast Al* → *2* (*redesign tank*) → *3* (*other changes*)

Propagation Extent





- Propagation extent had log-linear distribution
  - Rarely exceeded 2 generations of descendants
  - Never exceeded 5 generations of descendants

Design for Flexibility: Example

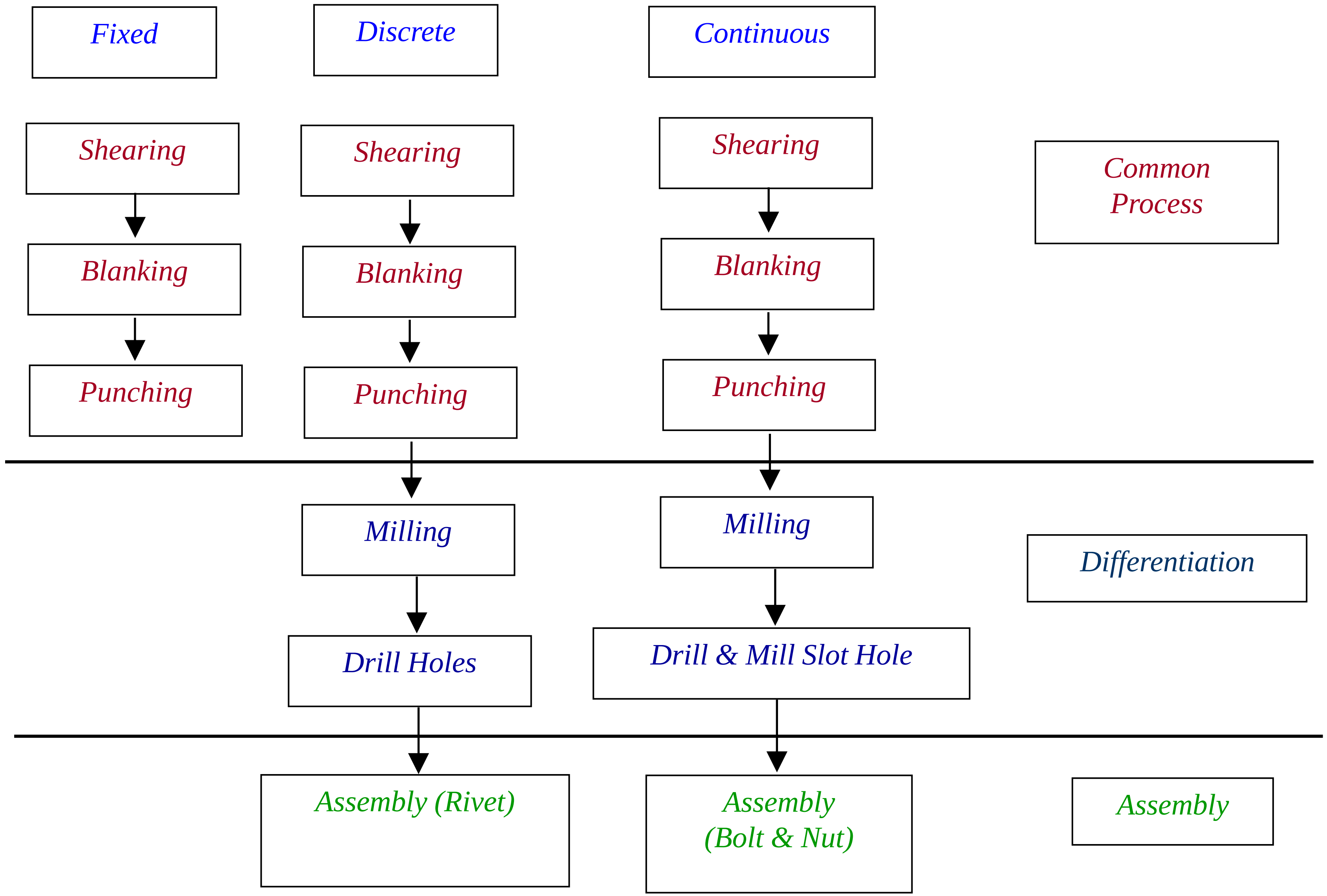
Fixed Discrete Continuous

Flexibility can be embedded in the design or manufacturing process or in the product itself or both.

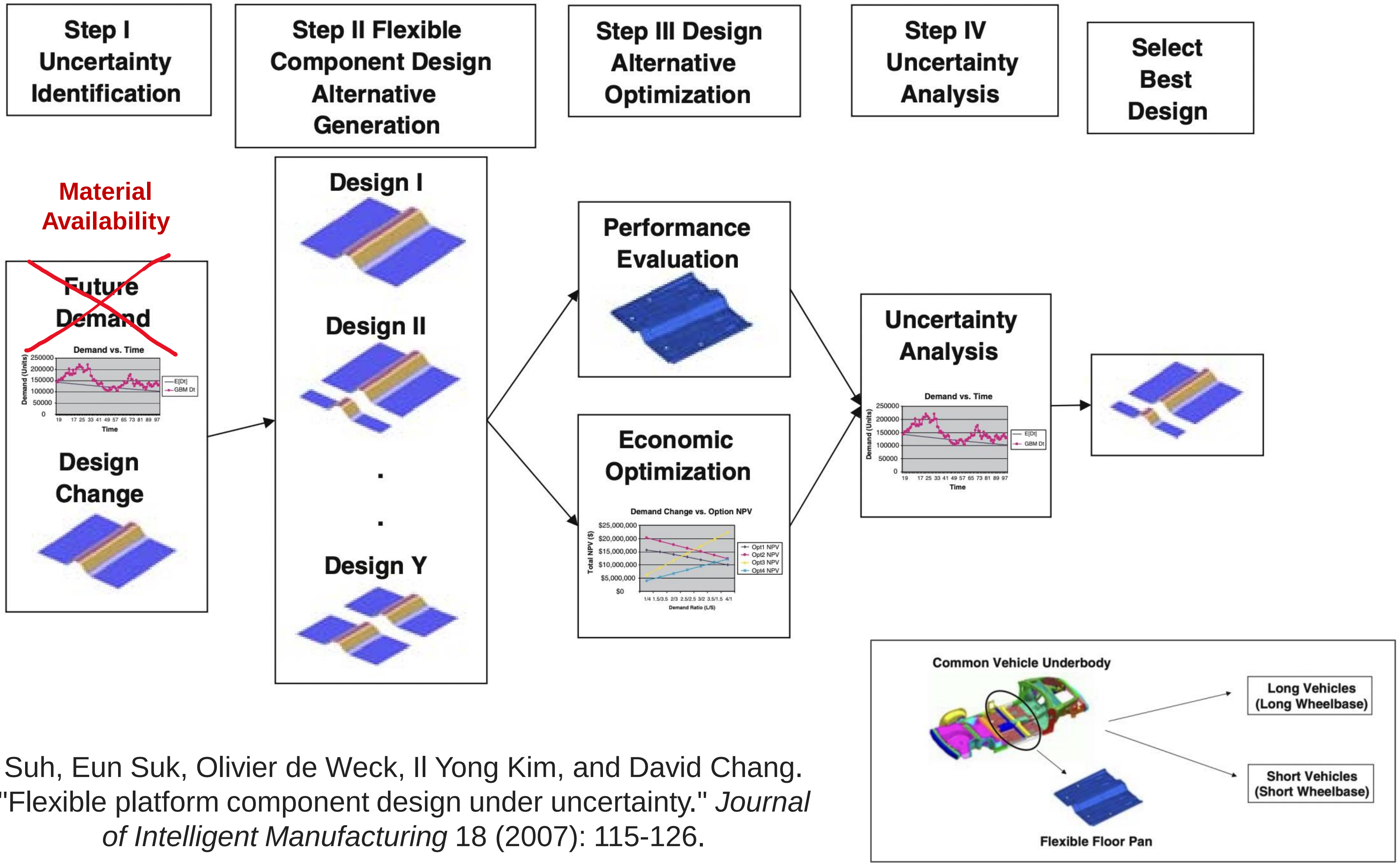
Three Component Manufacturing Strategies are Considered:

- *Fixed Length: No Flexibility*
- *Discrete Length: Rivet Secured, Manufacturing Flexibility*
- *Continuous Length: Bolt Secured, Manufacturing Flexibility*

Manufacturing Process Comparison



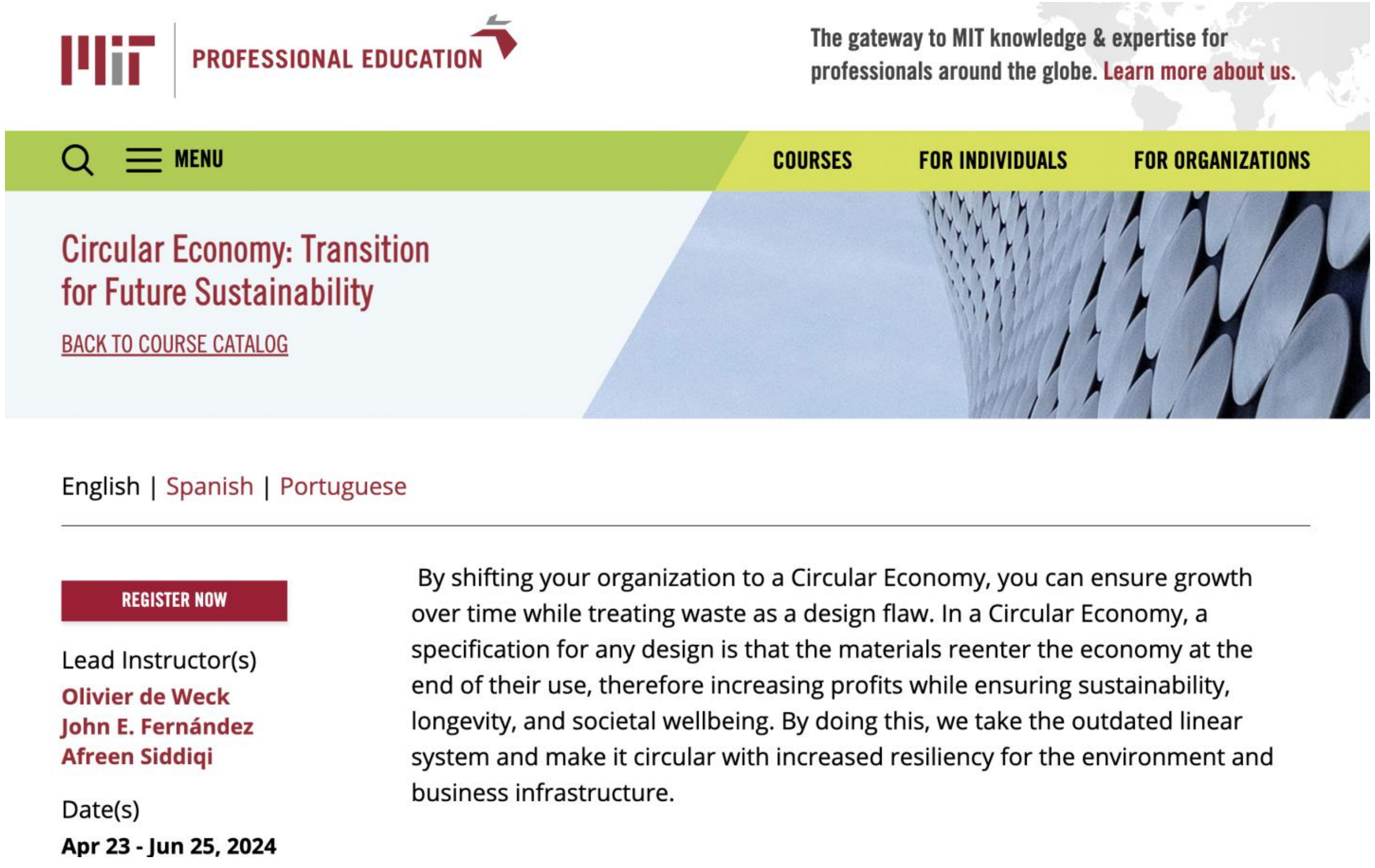
Design for Flexibility Framework



Suh, Eun Suk, Olivier de Weck, Il Yong Kim, and David Chang. "Flexible platform component design under uncertainty." *Journal of Intelligent Manufacturing* 18 (2007): 115-126.

Towards a Circular Economy

"R2 looks to significantly increase the ability to produce critical items at point of need ***utilizing scavenged material."***



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Olivier de Weck
John E. Fernández
Afreen Siddiqi

Date(s)

Apr 23 - Jun 25, 2024

By shifting your organization to a Circular Economy, you can ensure growth over time while treating waste as a design flaw. In a Circular Economy, a specification for any design is that the materials reenter the economy at the end of their use, therefore increasing profits while ensuring sustainability, longevity, and societal wellbeing. By doing this, we take the outdated linear system and make it circular with increased resiliency for the environment and business infrastructure.

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