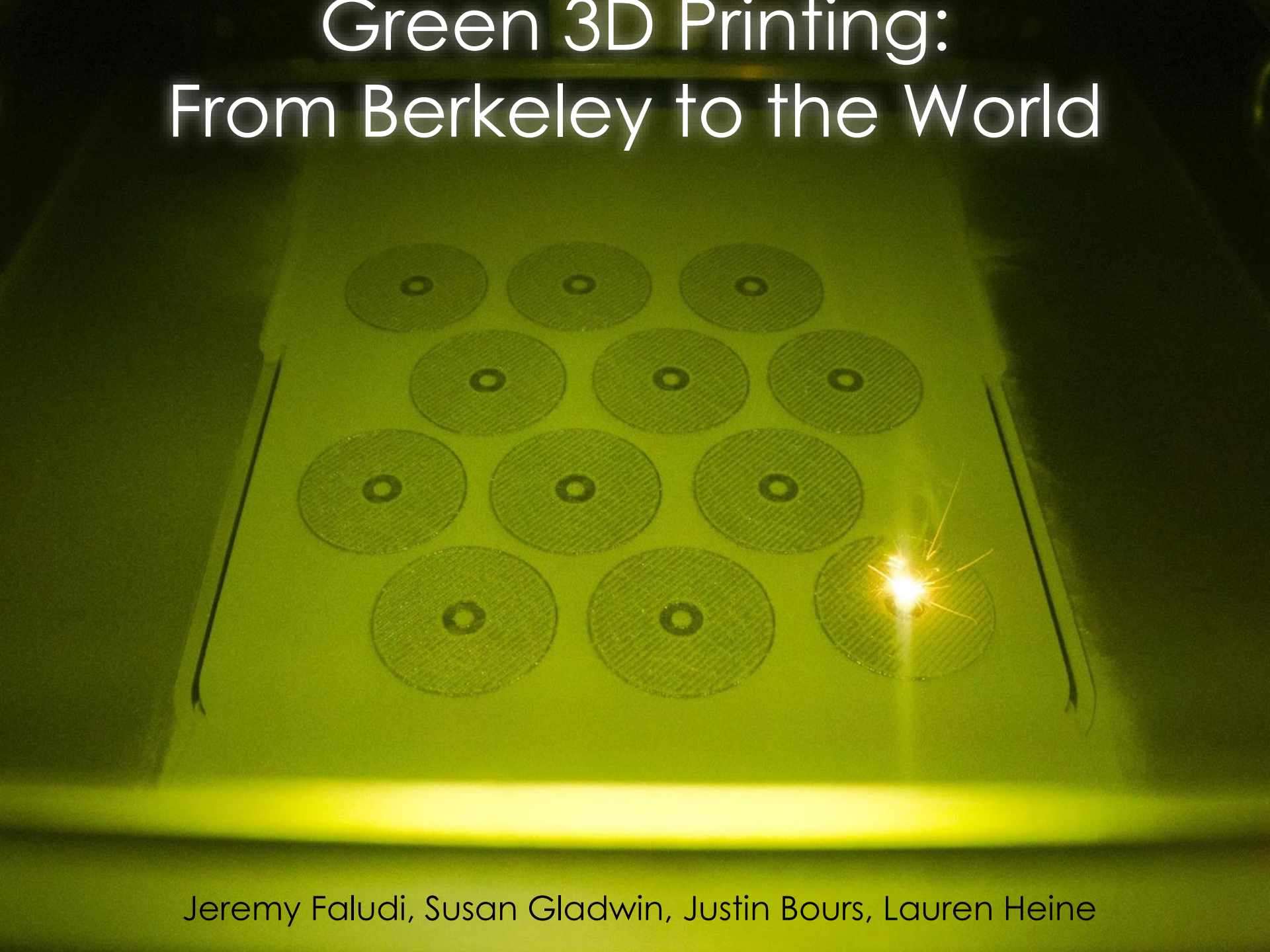
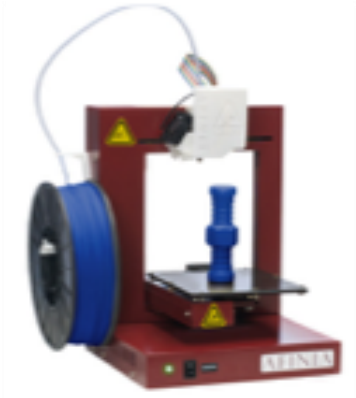
Green 3D Printing: From Berkeley to the World



Jeremy Faludi, Susan Gladwin, Justin Bours, Lauren Heine

Jeremy Faludi

Printing Process Variety

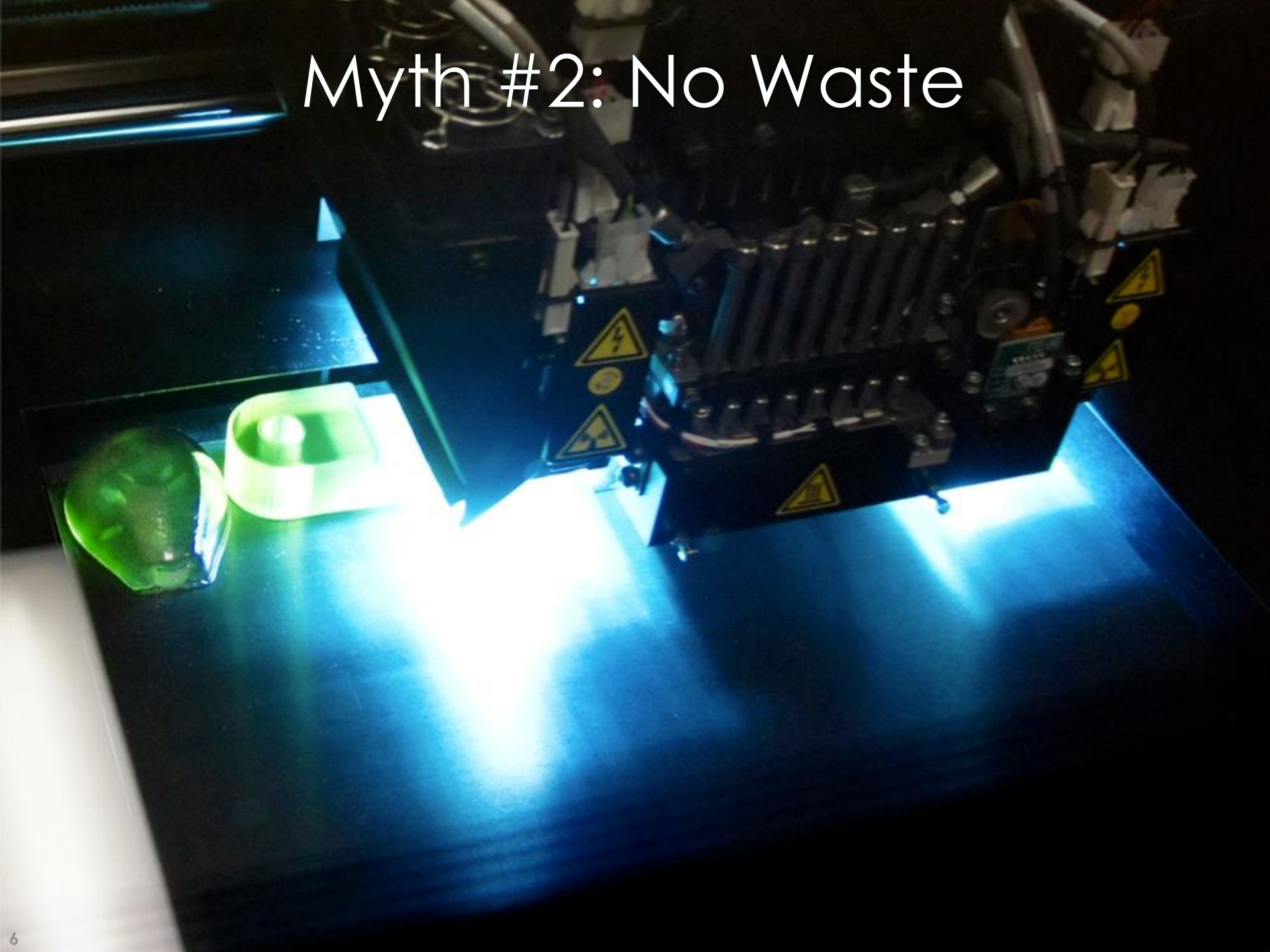


images from renishaw.com, 3Dsystems.com, stratasys.com, afinia.com, typeamachines.com, engadget.com

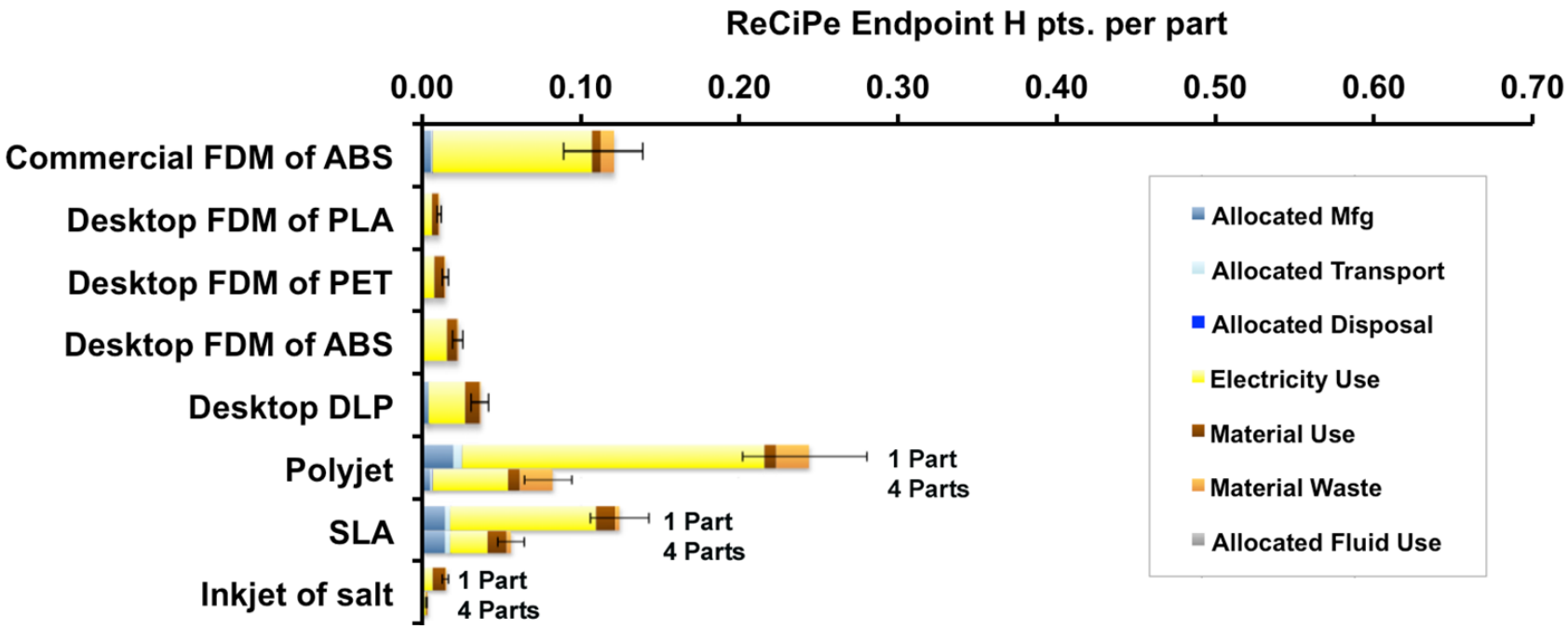
3D Printing Myths vs. Facts

Myth #1: No Transportation

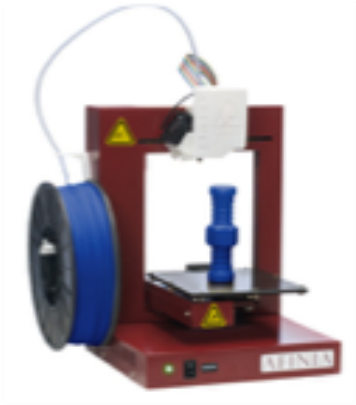
Myth #2: No Waste



Energy is Main Impact



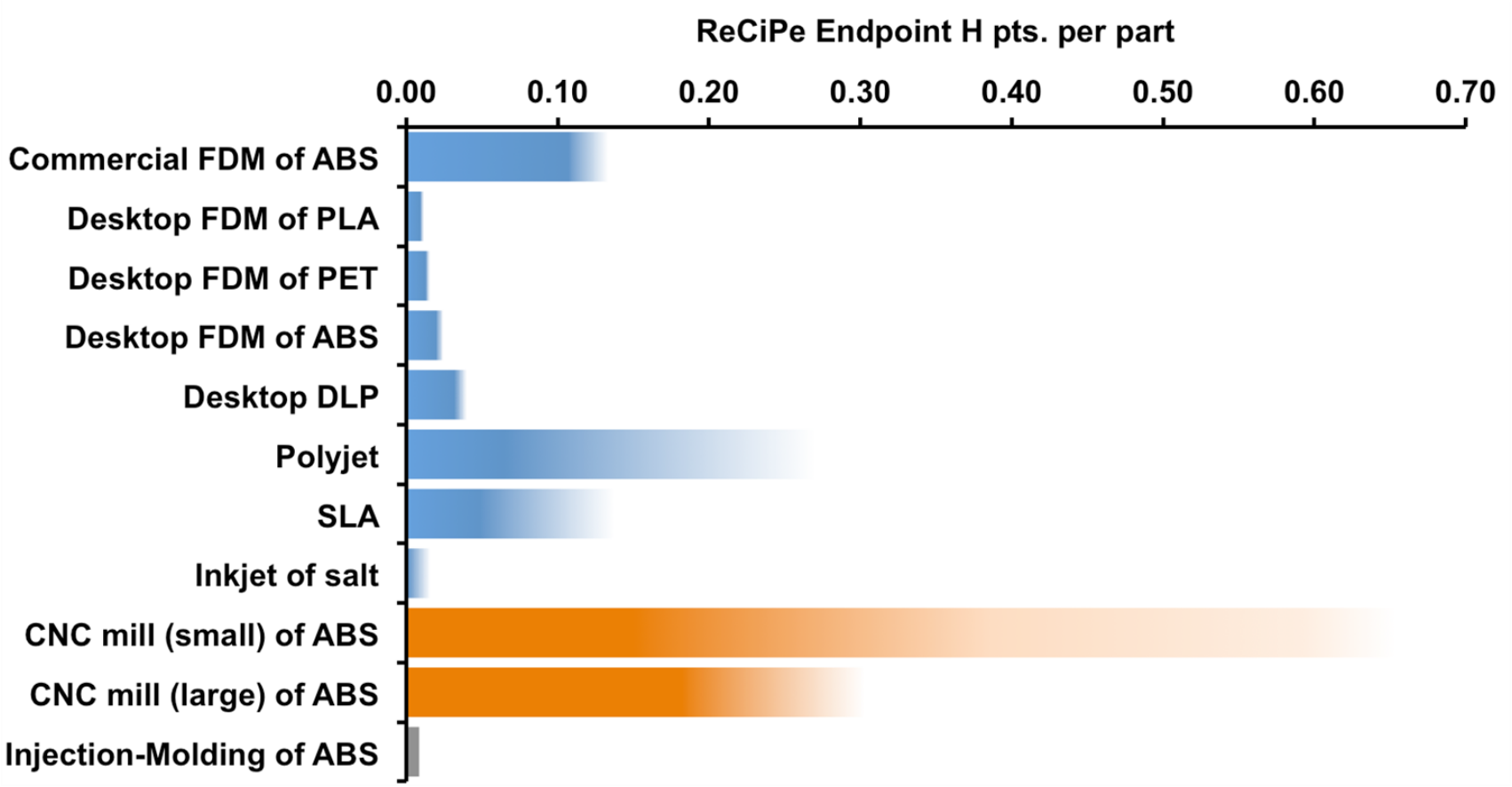
Is 3D Printing Green? It Depends…



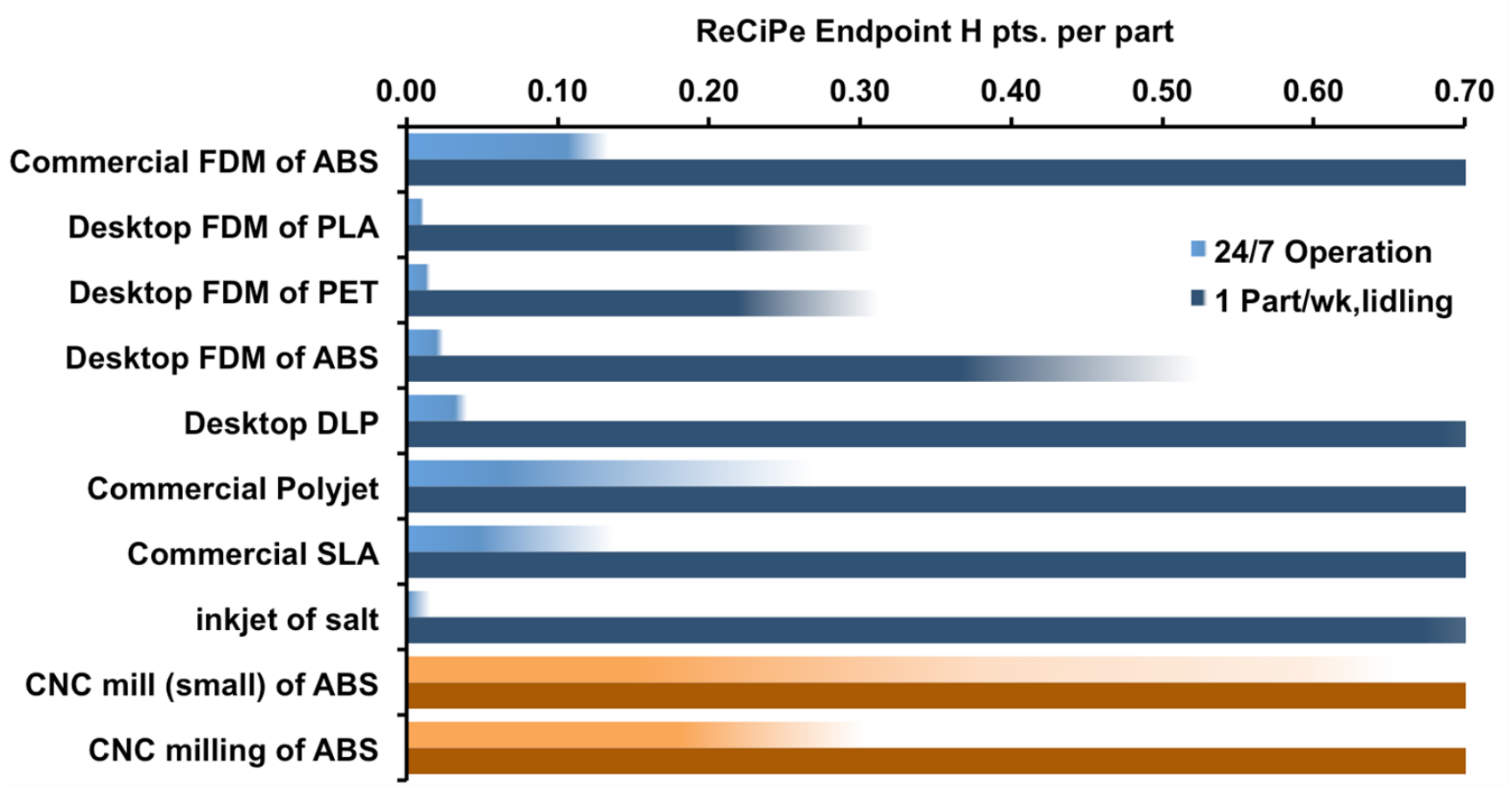
images from renishaw.com, 3Dsystems.com, stratasys.com, afinia.com, typeamachines.com, engadget.com

Is 3D Printing Green? It Depends…

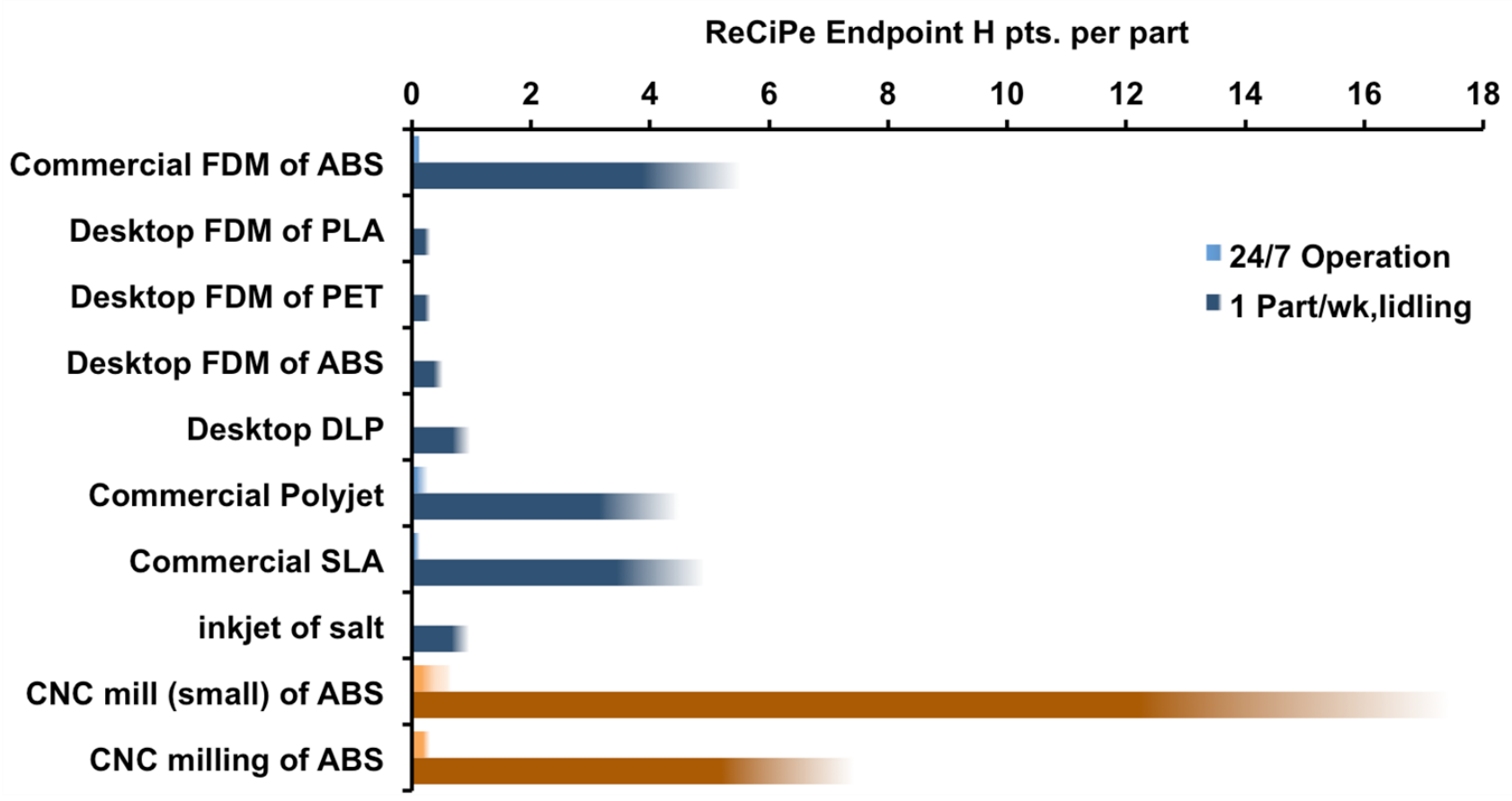
Utilization



Utilization



Utilization



Obstructing Circular Economy

Irreversible Materials

Mixing Materials Inseparably

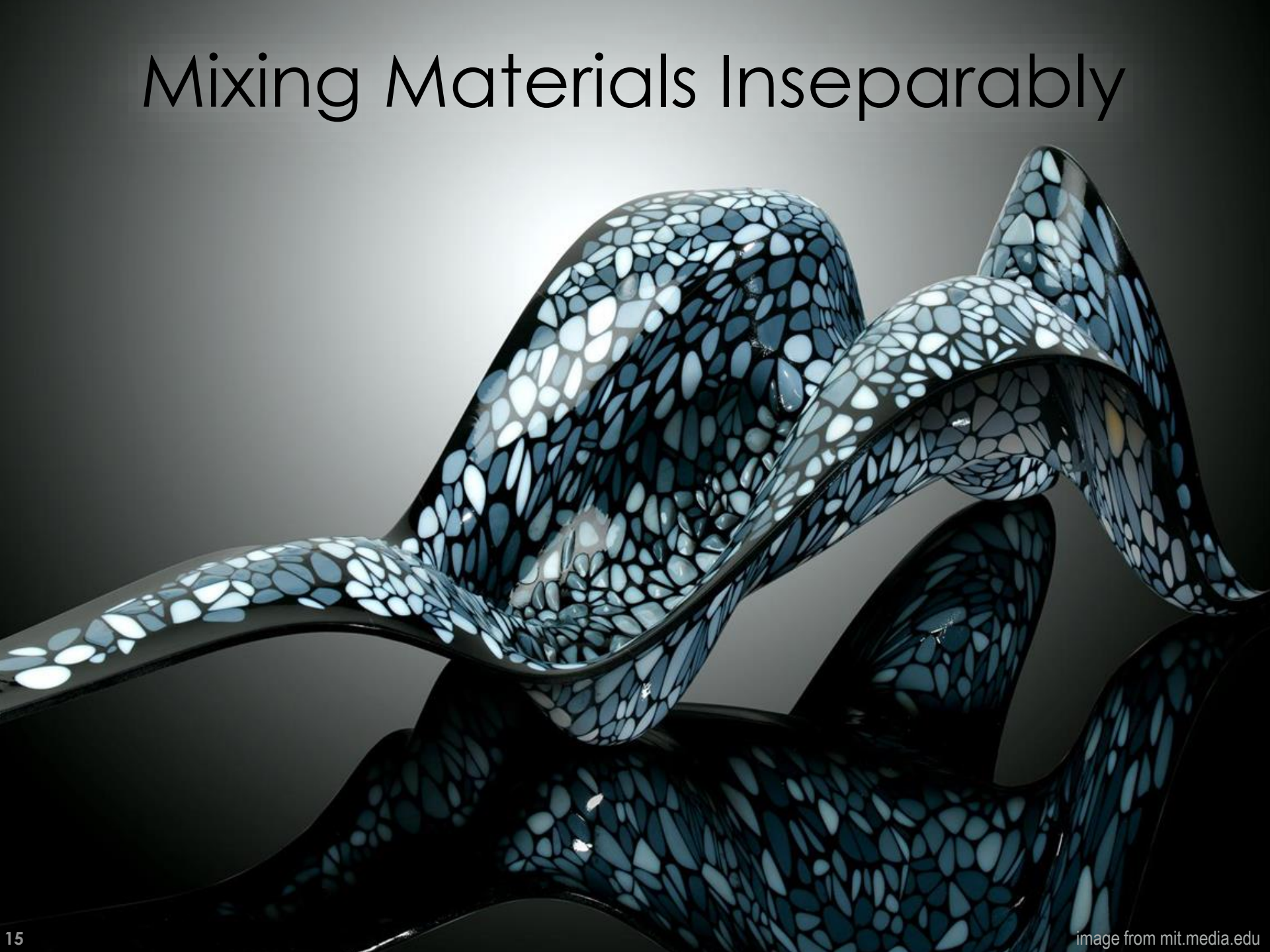


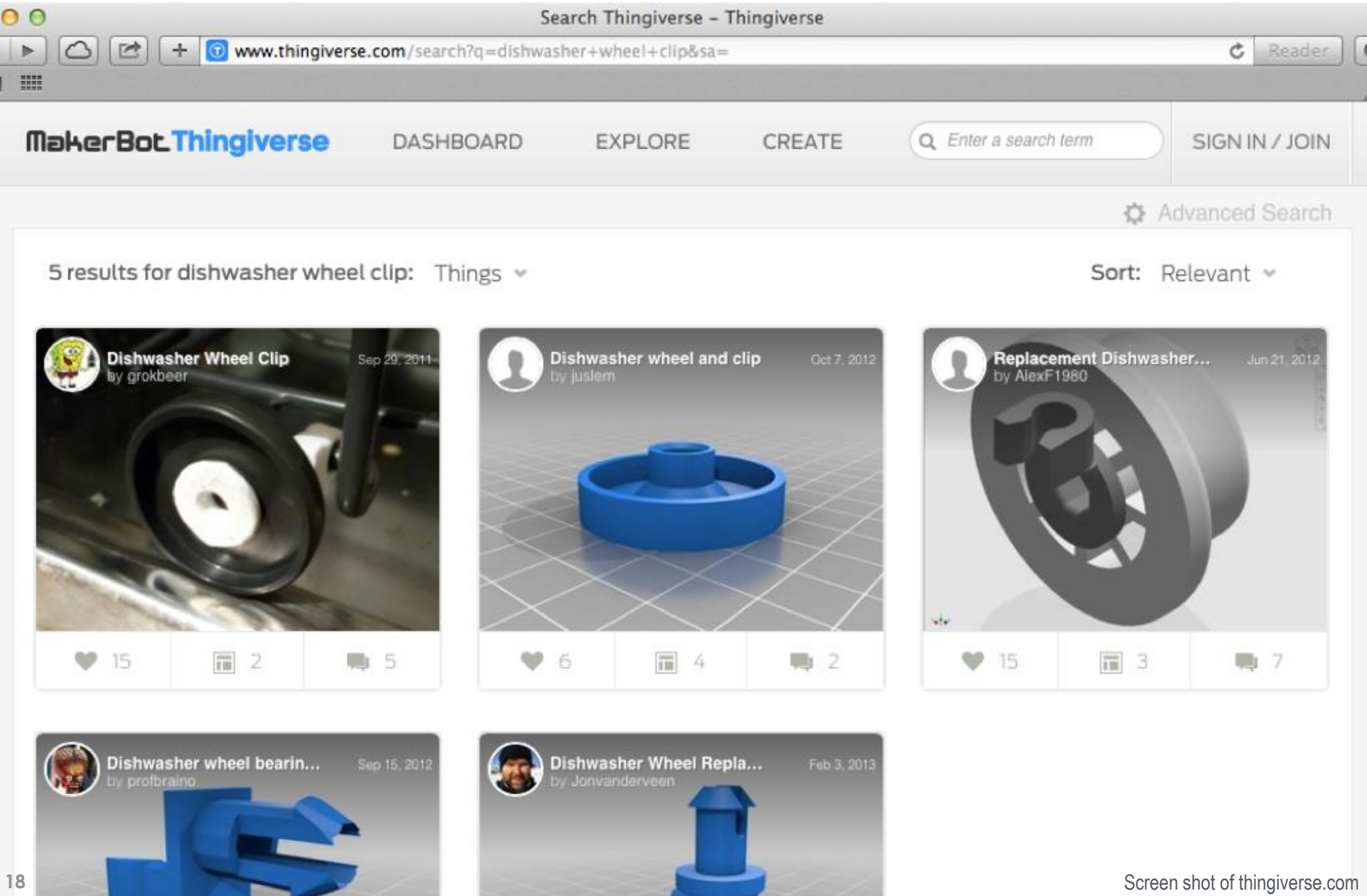
image from mit.media.edu

Enabling Circular Economy

Efficient Vehicles

image from bloomberg.com

Repair



Screen shot of thingiverse.com

Democratize Production

image from 3dprintingindustry.com

Align Economic Incentives

Material use = $

Complexity ≈ free

Enable Green Materials?

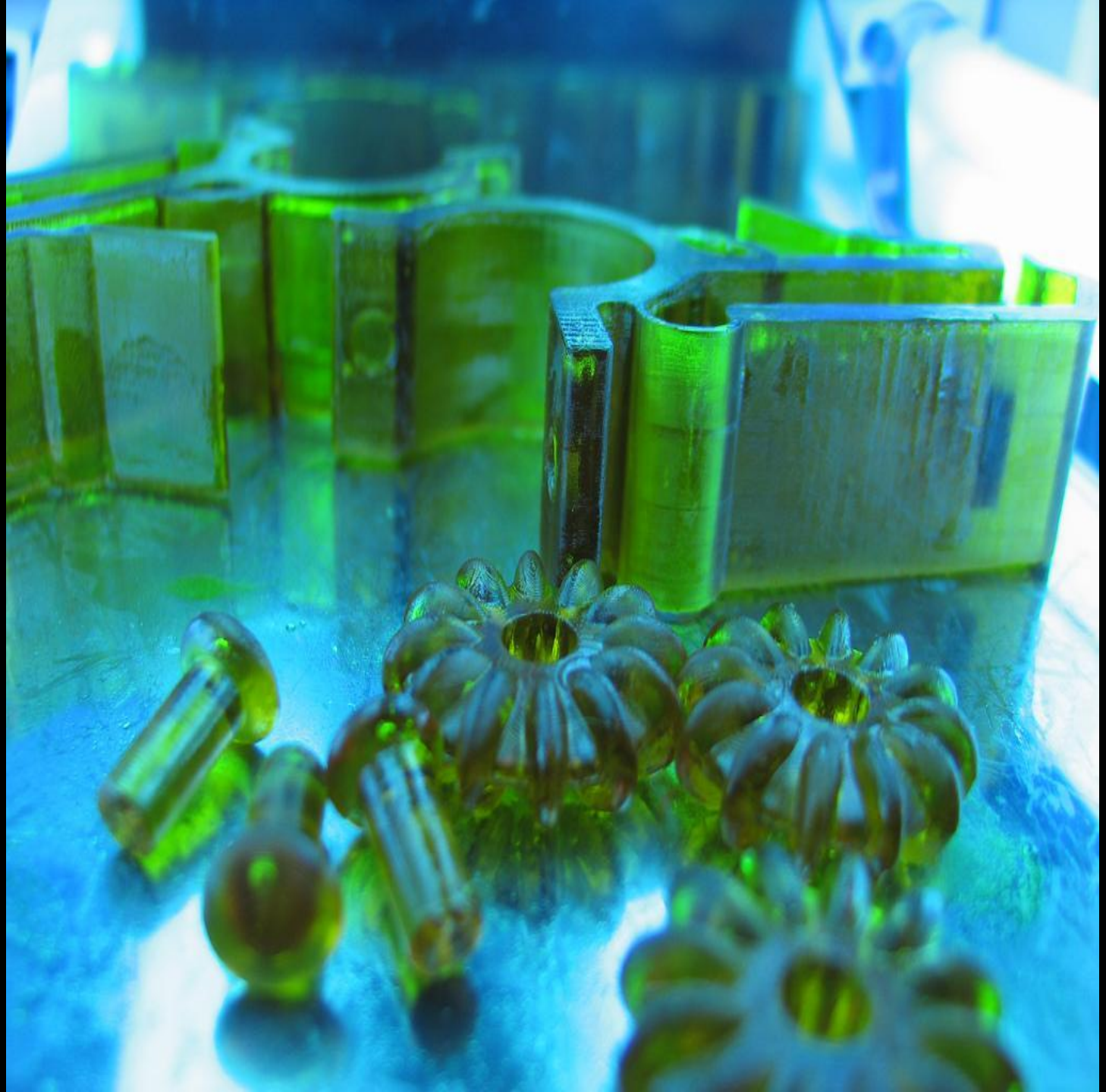
image from mit.edu

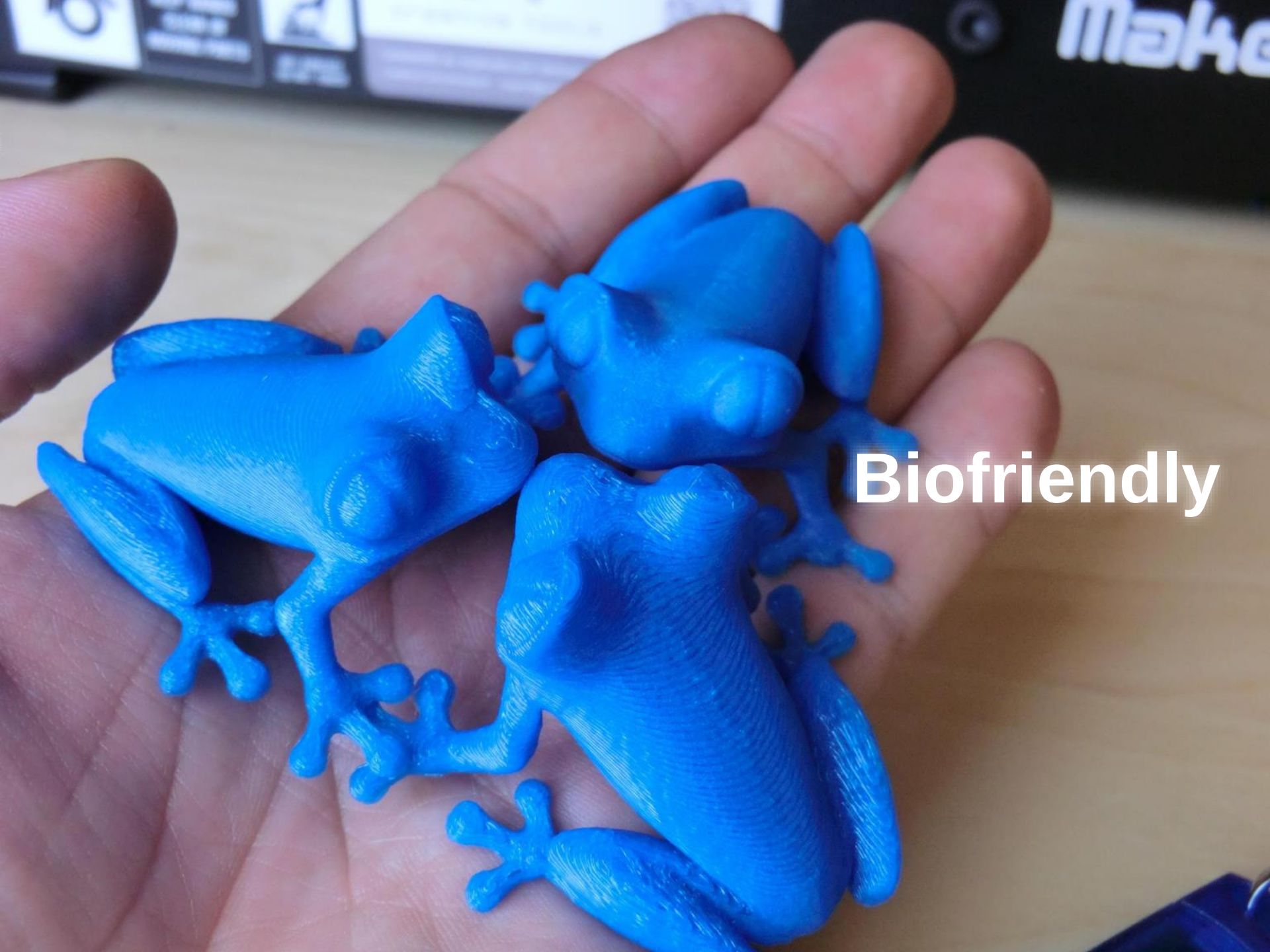
The Next Production Revolution

IMPLICATIONS FOR GOVERNMENTS AND BUSINESS

OECD

Susan Gladwin




Biofriendly

The hazards of Stereolithography (SLA) Resins

Photoinitiator (0.4%)

Reactive Oligomers (79.55%)

Reactive Monomer (19.88%)

UV-blocker (0.16%)

Reproductive toxicant

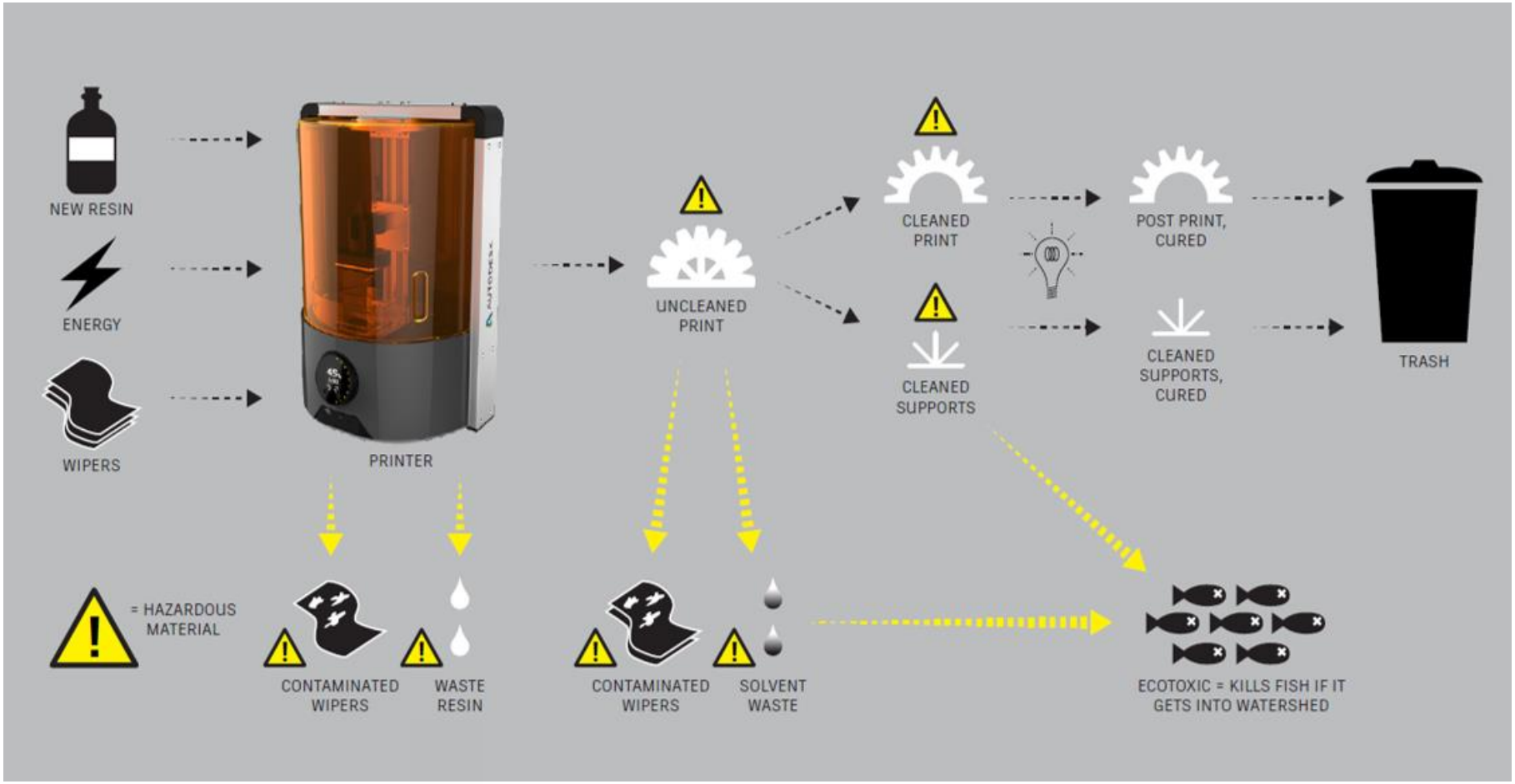
Eye irritant

Skin irritant

Aquatic toxicant

Skin sensitizer

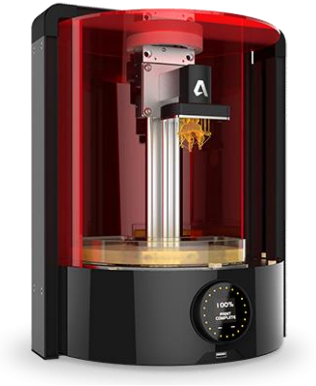
The life cycle for SLA Printing



Ubiquity of 3D Printing

Industrial. $100,000s+

1990’s



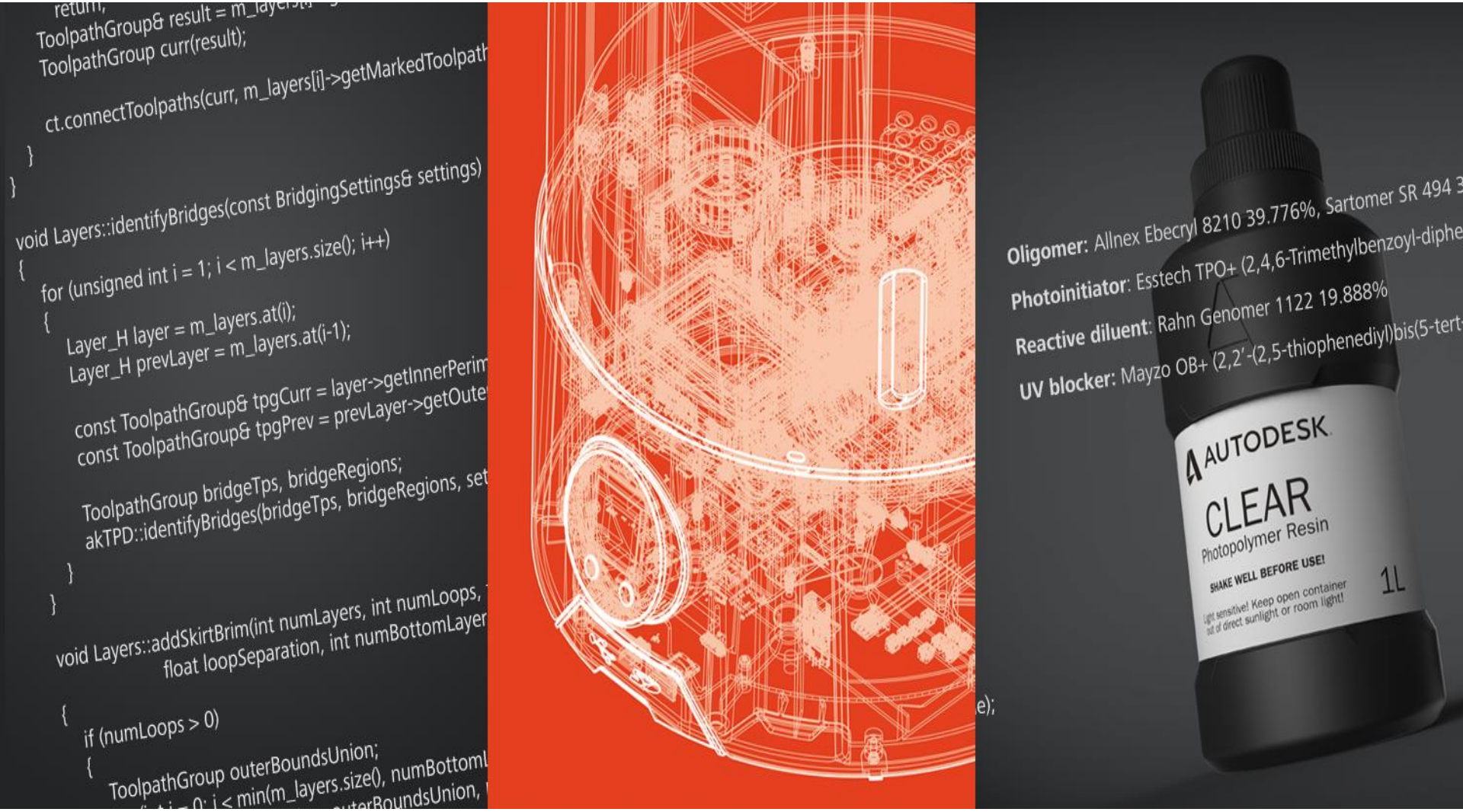
Light Industrial. $1,000s+

2015

$100s

Now

Open+ Creative Commons: code, CAD, materials recipe



Collaborators

BERKELEY CENTER FOR GREEN CHEMISTRY

AUTODESK®

BIOMIMICRY INSTITUTE

Northwest Green Chemistry

Justin Bours

Greener Solutions Class Methods

Explore

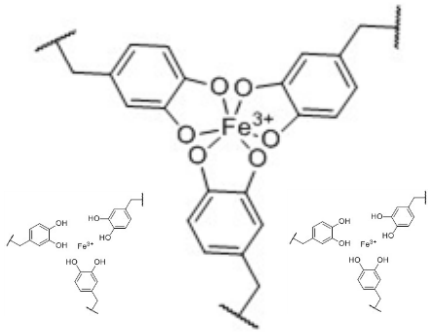
Bio-inspired

Approaches

Identify

Alternative

Resin Materials



Evaluate

New Resin

Materials

Three Tiers of Disruption

I. REPLACING THE PHOTOINITIATOR

Strategy A: Curcumin & Riboflavin

II. MODIFYING ACRYLATE-BASED RESINS

Strategy B: Triglycerides

Strategy C: Chitosan

III. pH PHOTOINITIATED RESINS

Strategy D: Calcite

Strategy E: Metal Ligand Complexes

Hazard Comparisons

Strategy	A: New Photo-initiators	B: Triglyceride acrylates	C: Glycol Chitosan acrylates	D: Calcite Resin	E: Metal-ligand complex
Skin sensitization	⚪	⚪	⚪	⚪	⚪
Eye Irritation	🟢	🔴	🟢	🔴	🔴
Skin Irritation	🔴	🟢	🟢	🔴	🔴
Aquatic Toxicity	🔴	🔴	🔴	🔴	🔴
Reproductive Toxicity	🟢	⚪	⚪	🟢	🟢

KEY: ⚪ *Data Gaps* 🔴 *Identified Hazard* 🟢 *Decreased Hazard*

Autodesk + BCGC Collaborative Publication

JOURNAL OF INDUSTRIAL ECOLOGY

METHODS, TOOLS, AND SOFTWARE | Open Access

Addressing Hazardous Implications of Additive Manufacturing: Complementing Life Cycle Assessment with a Framework for Evaluating Direct Human Health and Environmental Impacts

Justin Bours, Brian Adzima, Susan Gladwin, Julia Cabral, Serena Mau

First published: 27 May 2017 | https://doi.org/10.1111/jiec.12587 | Cited by:3

https://onlinelibrary.wiley.com/doi/full/10.1111/jiec.12587

Framework Approach VS Other Analyses

ONLY

LCA

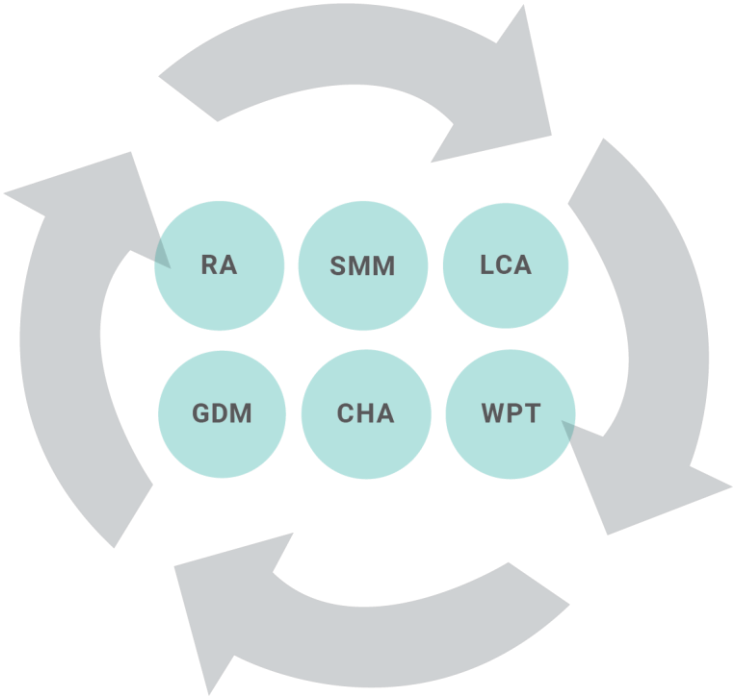
ONLY

CHA

Underrepresentation of direct human health impacts

OUR APPROACH

Lack of life-cycle thinking



Curated, stepwise framework development

PHASE

1 Define life cycle stages → 2 What is in the material? → 3 Identify stakeholders, main impacts, and exposure pathways

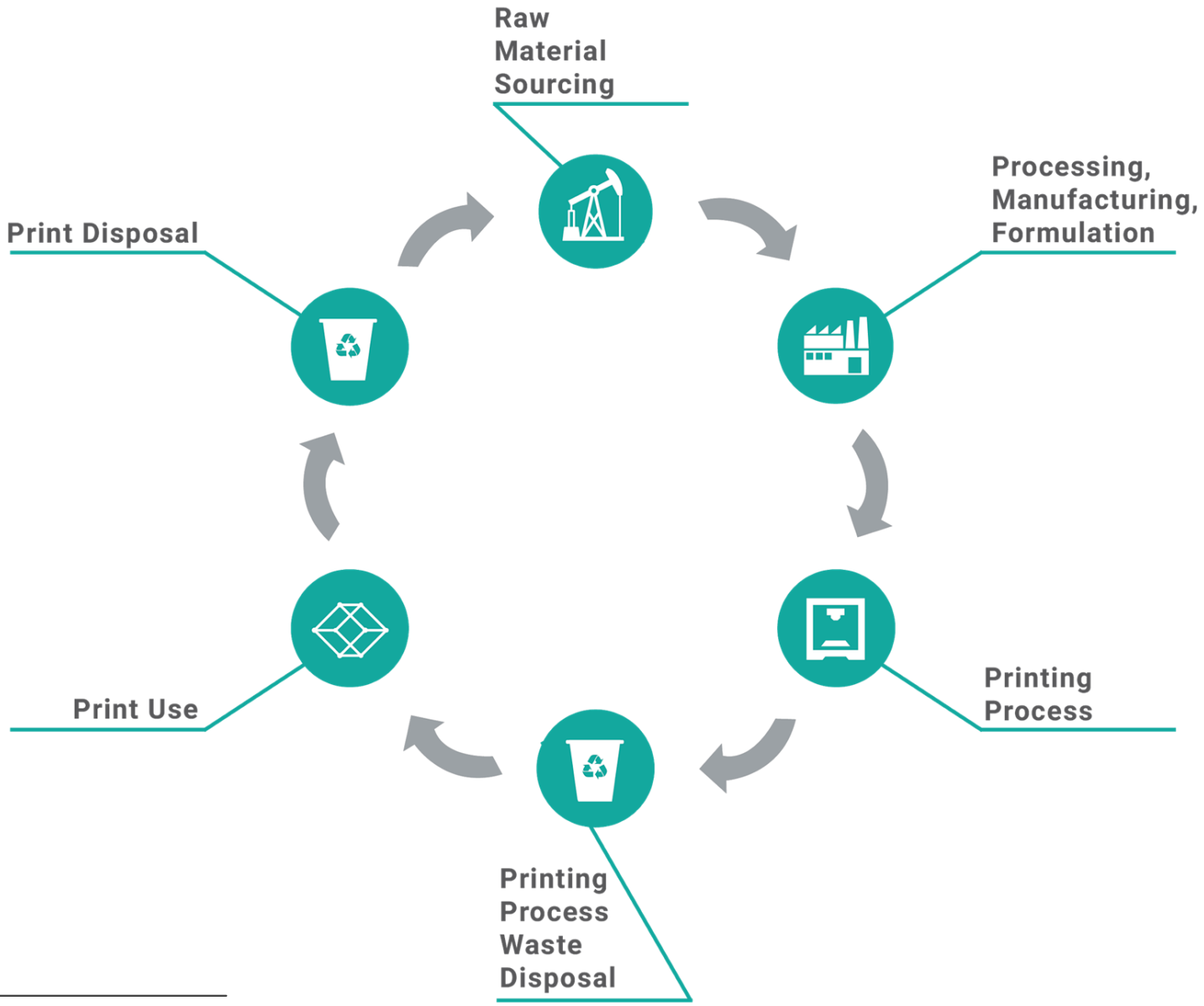
4 Identify criteria and metrics → 5 Identify the methodologies and data for evaluating criteria → 6 Establish a rating system

Northwest Green Chemistry

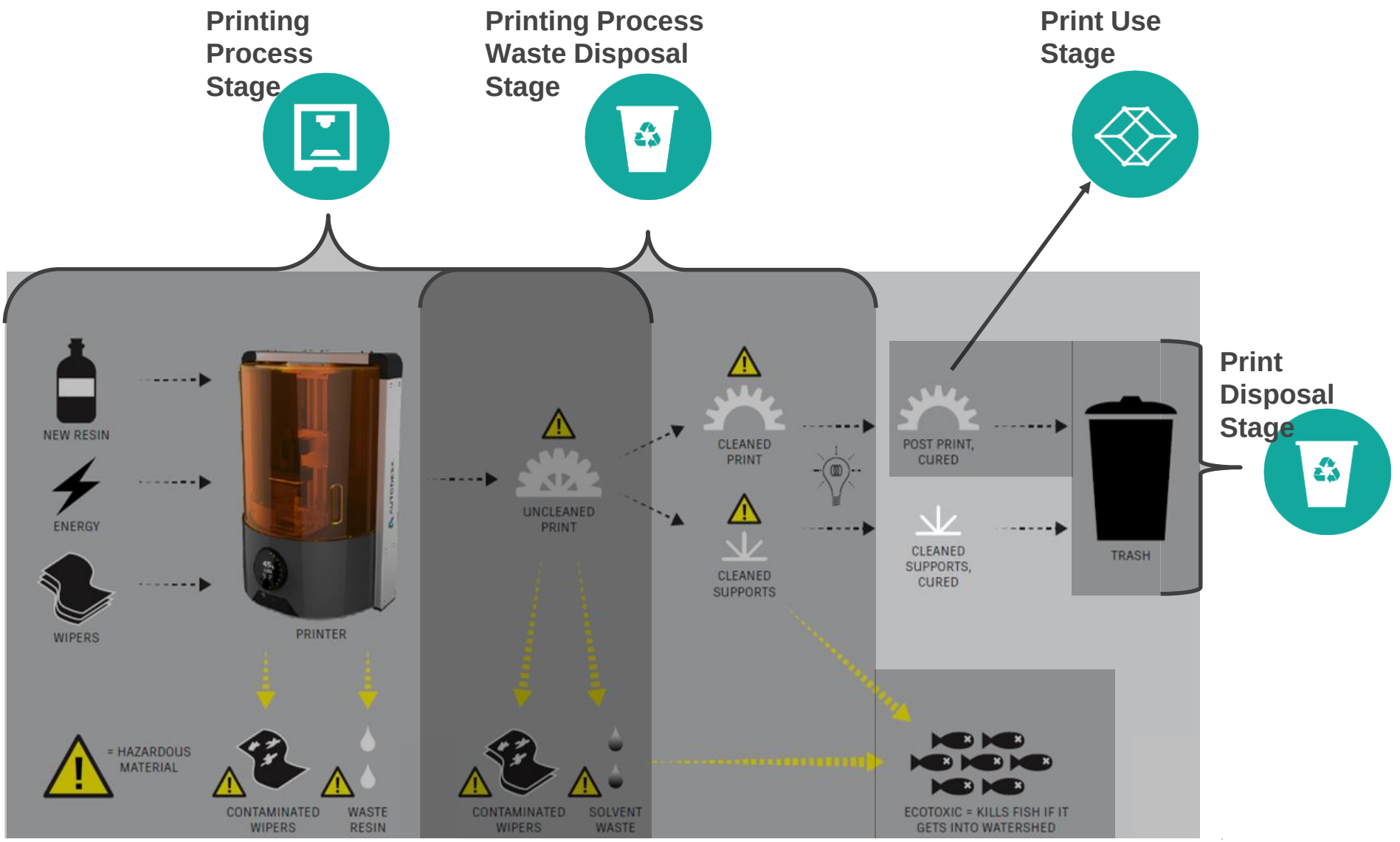
CERTIFIED cradletocradle

1	2	3

Defining the life cycle for SLA Printing



Defining the life cycle for SLA Printing



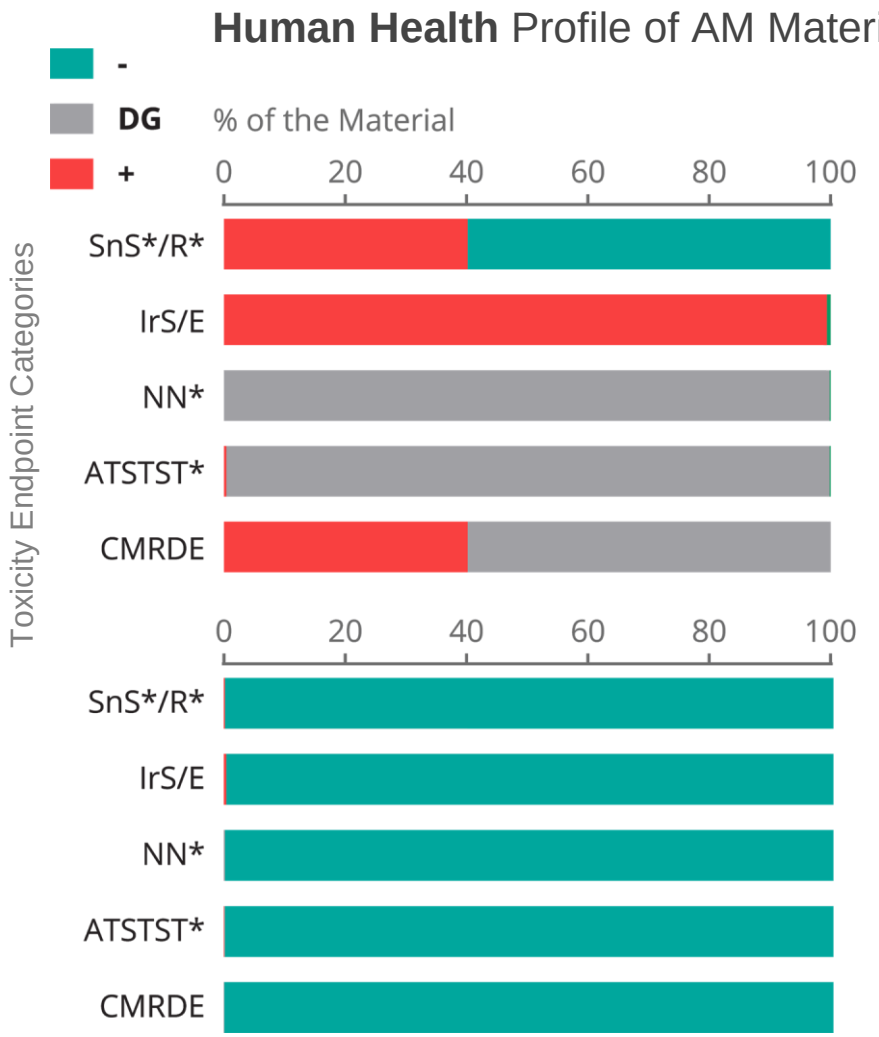
Identify criteria, metrics, methodologies

Criteria	Metrics	Methodology
Human Health Profile	CHA*	QCat, C2C
Physical Hazard	CHA	QCat, C2C
Post-Processing	Green Design, CHA	Waste, Electricity Usage, QCat, GreenScreen
Ultrafine Particles	CHA, RA**	QCat, C2C, Volume of particles
VoC Emissions	CHA, RA	QCat, GreenScreen, Volume of particles

PR48 is significantly more hazardous than PLA

Autodesk PR48

PL A



Printing Process Stage

PLA substantially outperforms Autodesk PR48*

Autodesk's PR48

Printing Process	0
Printing Process Waste Disposal	0
Print Use	1
Print Disposal	1
Overall	0.5

PL
A

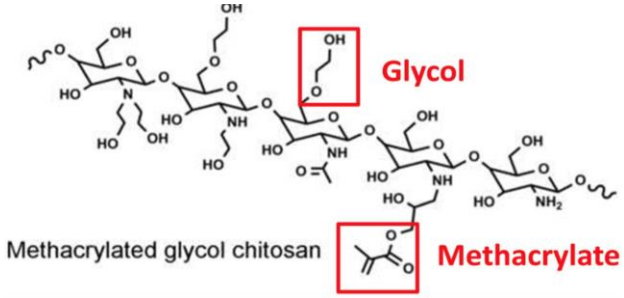
Printing Process	1
Printing Process Waste Disposal	2
Print Use	2
Print Disposal	2
Overall	1.75

*Comparing materials from similar technologies will likely result in closer ratings

Using framework to identify improved materials/processes

Autodesk's PR48

	Autodesk's PR48	Using an acrylate resin with a bio-derived backbone
Printing Process	0	1
Printing Process Waste Disposal	0	1
Print Use	1	2
Print Disposal	1	1
Overall	0.5	1.25



Arakawa, Christopher Kenji. "A Novel Photopolymerizable Chitosan Collagen Hydrogel for Bone Tissue Engineering," 2012. http://escholarship.org/uc/item/1wp7v2g2.pdf.

Autodesk blogs on this work

AUTODESK.

Netfabb Additive Manufacturing Blog

Towards Sustainable 'Biofriendly' Materials for Additive Manufacturing (Part 1 of 3)

Brian Sather November 18, 2015

(0) Save 0 0

Image (cropped here) courtesy of Jason Hollinger (CC BY 2.0)
By Michael Floyd and Susan Gladwin

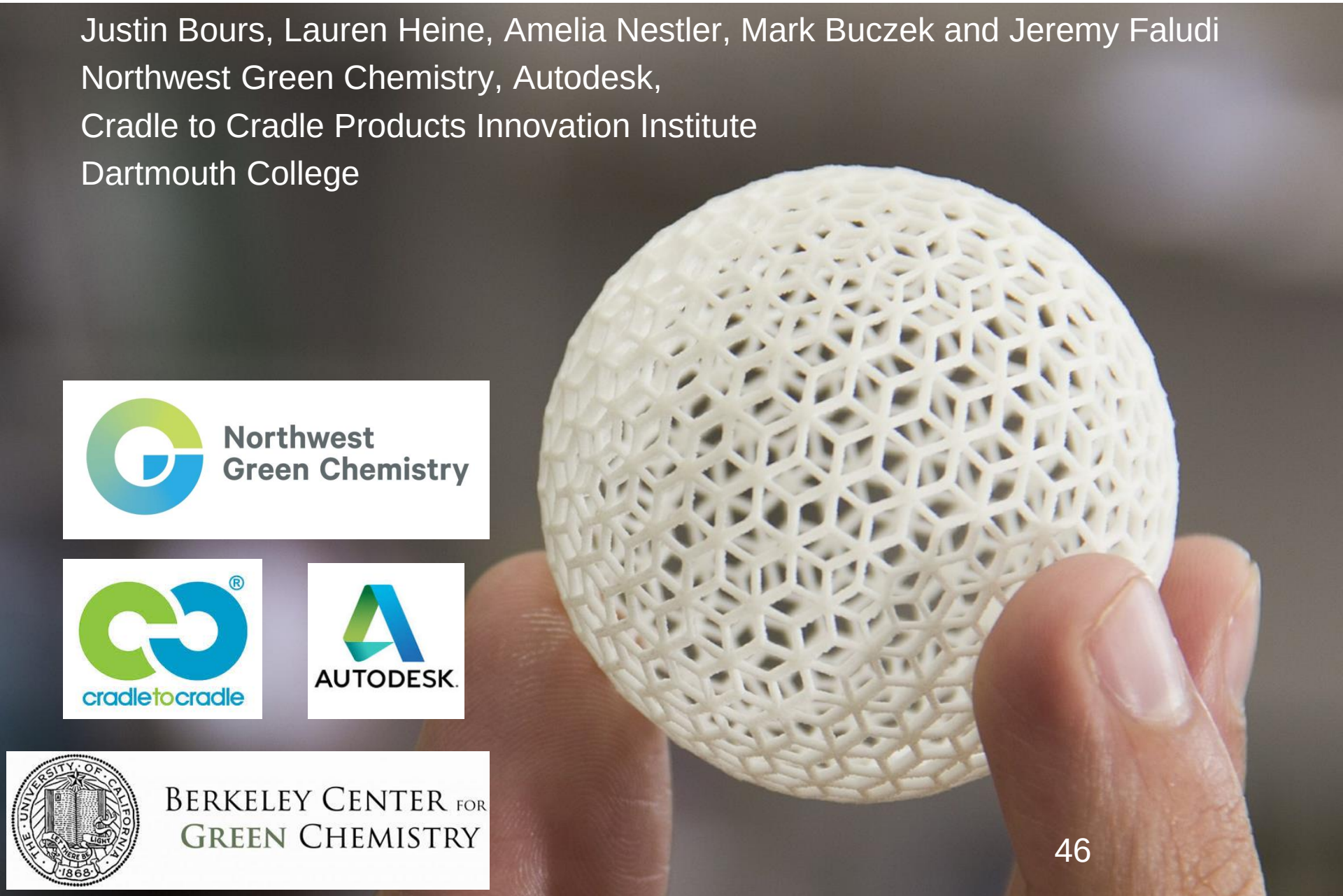
As the additive manufacturing industry grows and extends its reach, it becomes important to ask a number of related health, safety, and environmental questions. While the answers to some of these questions are currently unclear, we have only to look at

http://blogs.autodesk.com/netfabb/2015/11/18/towards-sustainable-biofriendly-materials-for-additive-manufacturing-part-1-of-3/

Lauren Heine

3D Printing Roundtable

Justin Bours, Lauren Heine, Amelia Nestler, Mark Buczek and Jeremy Faludi
Northwest Green Chemistry, Autodesk,
Cradle to Cradle Products Innovation Institute
Dartmouth College



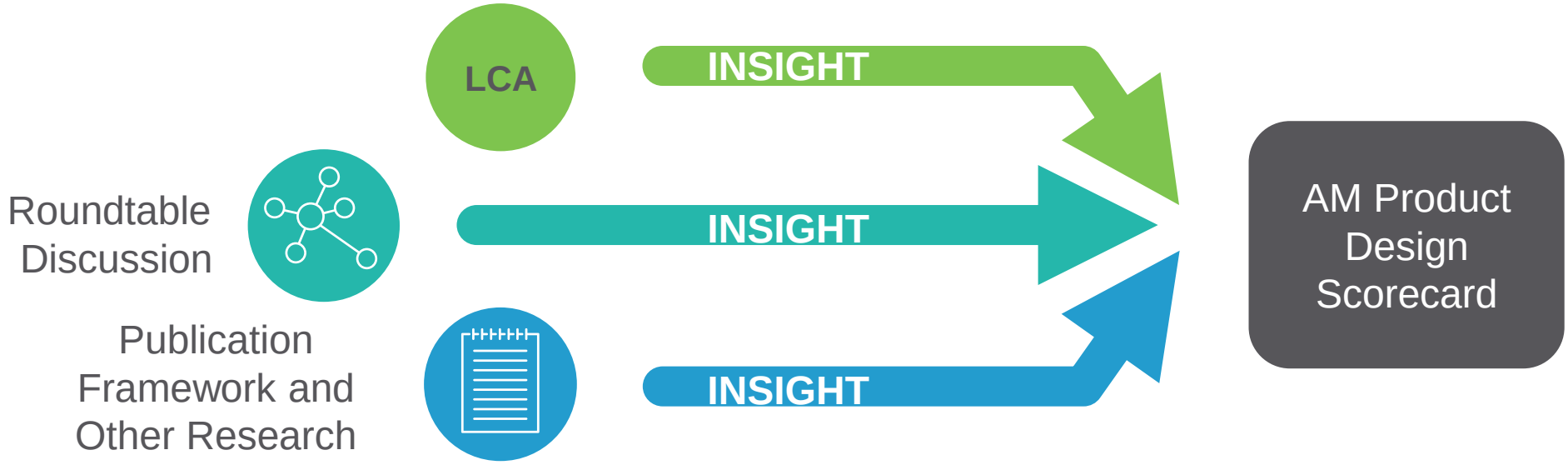
Northwest Green Chemistry

cradletocradle

AUTODESK.

BERKELEY CENTER FOR GREEN CHEMISTRY

Designing an AM Product Design Scorecard



Participants in the 3D Printing Roundtable

NGOs

- Northwest Green Chemistry
- Cradle to Cradle Products Innovation Institute
- Ellen MacArthur Foundation
- Green Chemistry and Commerce Council

Academia

- Berkeley Center for Green Chemistry
- University of California Irvine
- Universidad de Santiago de Chile, Alysia Garmulewicz
- Dartmouth College

Government

- US EPA
- WA State Department of Ecology
- Oregon Department of Environmental Quality

Printer/Software Manufacturers

- Autodesk
- XYZprinting
- Pollen AM
- Structo 3D

Material Manufacturers

- Clariant
- Covestro
- CPS Polymers
- Millipore-Sigma
- NatureWorks
- SABIC
- ZilaWorks

AM Users

- Lego

Consulting firms/Industry Expertise

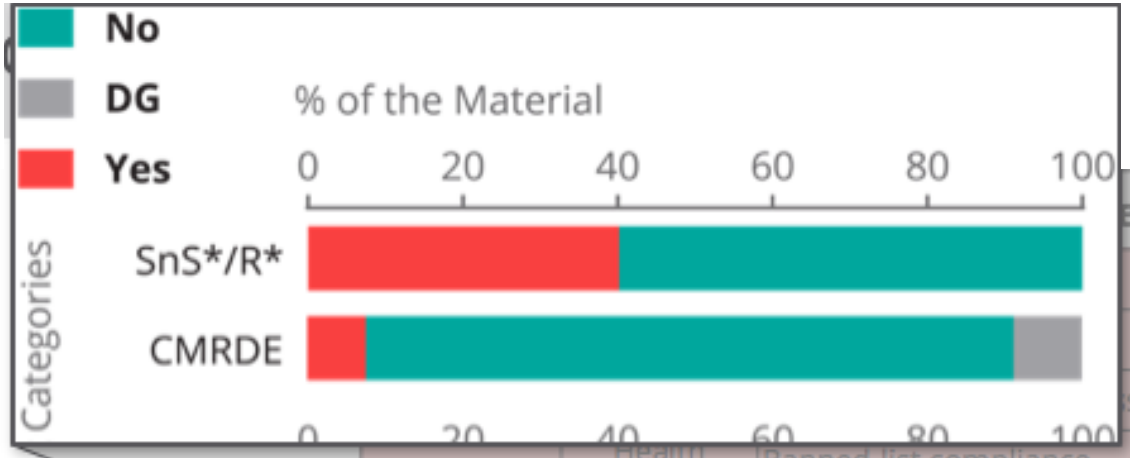
- Pre Sustainability Consultants

Participant Recommendations

- An appropriate assessment tool can support decision making for both:
  - **Material selection** and
  - **Product design**
- Results should be **simple** and **visual**
- There will always be **tradeoffs** and **imperfect information,**
  - Tradeoffs should be **transparent**
- **No one assessment tool** can provide all of the answers on sustainability; they need to be used together in a systemic way
  - Life cycle (impact) assessment
  - Chemical hazard assessment
  - Exposure assessment
  - Risk assessment
  - Circularity Assessment (Sustainable Materials Assessment)

Prototype: Printer Design Scorecard

Achievement Level	Category	Criteria		
Basic	Printing Energy	------ ---------- --- ------ -------- -- --- -------- --------	All	✓
		------ ---------- --- ------ -------- -- --- -------- --------	All	✓
	Printer Sharing	------ ---------- --- ------ -------- -- --- -------- --------	All	✓
	Material / Waste Minimization	------ ---------- --- ------ -------- -- --- -------- --------	All	✓
Silver	Printing Energy	------ ---------- --- ------ -------- -- --- -------- --------	All	
		------ ---------- --- ------ -------- -- --- -------- --------	IJ, LS, E	✓
	Printer Sharing	------ ---------- --- ------ -------- -- --- -------- --------	All	✓
		------ ---------- --- ------ -------- -- --- -------- --------	All	
	Material / Waste Minimization	------ ---------- --- ------ -------- -- --- -------- --------	All	
Gold	Printing Energy	------ ---------- --- ------ -------- -- --- -------- --------	All	
		------ ---------- --- ------ -------- -- --- -------- --------	All	
	Printer Sharing	------ ---------- --- ------ -------- -- --- -------- --------	All	✓
	Material / Waste Minimization	------ ---------- --- ------ -------- -- --- -------- --------	All	
		------ ---------- --- ------ -------- -- --- -------- --------	All	



Printer Material

			All	✓
			All	✓
			All	✓
		Banned-list compliance	All	✓
Silver	Material Reutilization	Medium recycled content use	All	✓
		High recyclability of material	All	✓
		Formulation is 90 % assessed	All	
	Material Health	Formulation contains < 10 % CMRDEs	All	
		Thermal decomposition products are known	IJ, LS, E	✓
		Non-hazardous post-processing	All	
		Medium emissions of nanoparticles	All	
Gold	Material Reutilization	High recycled content use	All	
		Reprintability of material	All	
		Durability of material	All	
	Material Health	100 % assessed formulation	All	
		Formulation contains < 0.1 % CMRDEs	All	
		Low emissions of nanoparticles	All	
	LCA	LCA of material scores < X ReCiPe Endpoint H pts/kg	All	

Greater scope–more thorough assessment

Printer Material

Printer Design

Printer Operations

Social Impacts

How toxic is material?

What are the emissions?

How much energy?

Designed to minimize failed prints?

Share to avoid idle time?

Minimize support material?

Improve economic opportunity?

Impact on communities?

Emergent Activities

- Research in collaboration with OR DEQ (proposed)
  - What is extent of the use of Additive Manufacturing in Oregon?
  - What are key activities and materials of concern
  - Where are opportunities for intervention
- Development of a Green Design and Assessment Framework (NGC with WA DOE)
  - Address each life cycle stage
  - Design with the end in mind
  - Principle-based
  - Consider hazard, exposure, life cycle impacts
- Future developments of the Scorecard
  - Scoping
  - Funding
  - Participant champions

Tools: (1) Chemical Inventory (2) Chemical Hazard Assessment (3) Exposure Assessment (4) Stakeholder Considerations (5) Life Cycle Considerations (6) Decision Analysis

Panel Discussion

Thank you! Any questions?