

Going Green EcoDesign2021, December 1-3, 2021

The 12th Int. Symp. on Environmentally Conscious Design and Inverse Manufacturing



# Applying Regenerative Sustainability Principles in Manufacturing

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**Proceedings now available online:**

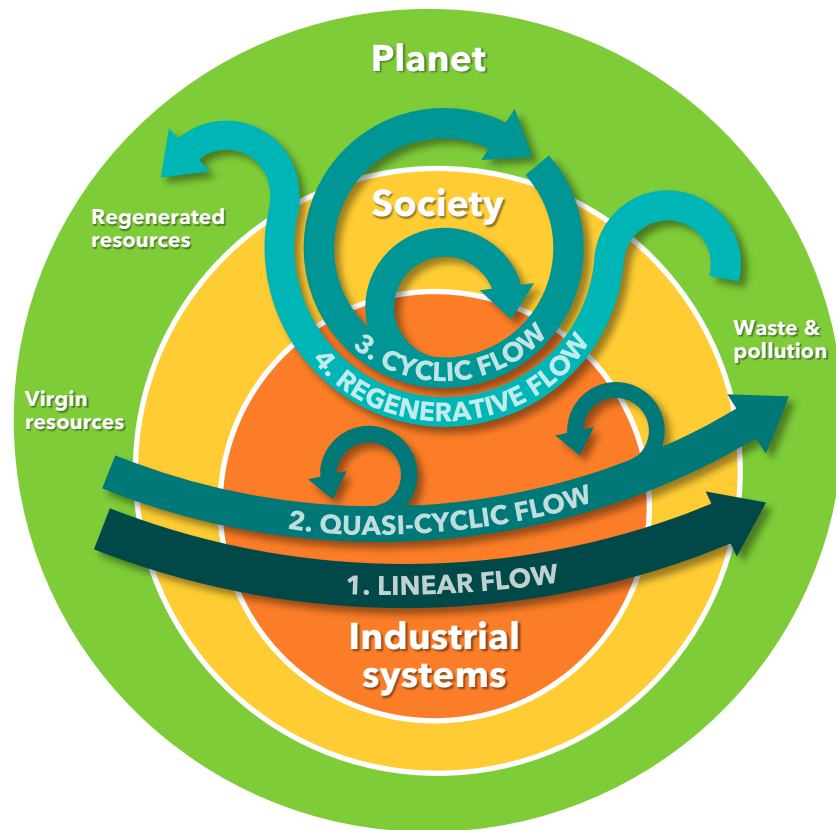
Despeisse, M. (2023). Applying Regenerative Sustainability Principles in Manufacturing. In: Fukushige, S., Kobayashi, H., Yamasue, E., Hara, K. (eds) EcoDesign for Sustainable Products, Services and Social Systems I. Springer, Singapore.  
[DOI: 10.1007/978-981-99-3818-6\\_10](https://doi.org/10.1007/978-981-99-3818-6_10)



# From less bad to more good

**Principle 1:**  
Sourcing materials,  
energy and water to  
promote conservation

**Principle 2:**  
Respecting  
regeneration rate



**Principle 3:**  
Preventing and  
mitigating harmful  
effects to promote  
preservation

**Principle 4:**  
Respecting  
assimilation  
capacity

# Proposed 12 principles for regenerative sustainability in manufacturing



## Principle 1. Source materials, energy and water to promote conservation

→ use renewable, non-toxic, and locally abundant resources

## Principle 2. Respect resource regeneration rate

→ use industrial processes that do not exceed ecosystems' renewal capacity

## Principle 3. Prevent and mitigate harmful effects to promote preservation

→ eliminate, minimise and treat waste/emissions

## Principle 4. Respect the assimilative capacity

→ use industrial processes that do not exceed ecosystems' absorption capacity

## Principle 5. Restore natural resource flows locally

→ use industrial processes that restore local ecosystems' health through decontamination and purification

## Principle 6. Regenerate damaged resources in products

→ use processes, and systems that reverse harm/recapture harmful substances

## Principle 7. Enable eco-efficient and circular resource flows locally

→ design and operate processes and systems that increase efficiency/reduce energy-matter throughput and increase circularity

## Principle 8. Maximise value creation through eco-efficient processes

→ design and operate processes and systems that efficiently create value to meet minimum requirements

## Principle 9. Retain and maintain value embedded in products

→ design and operate processes and systems for durability and reparability

## Principle 10. Recapture value embedded in products

→ design and operate processes and systems that capture end-of-life products, components, and materials to give them a new life

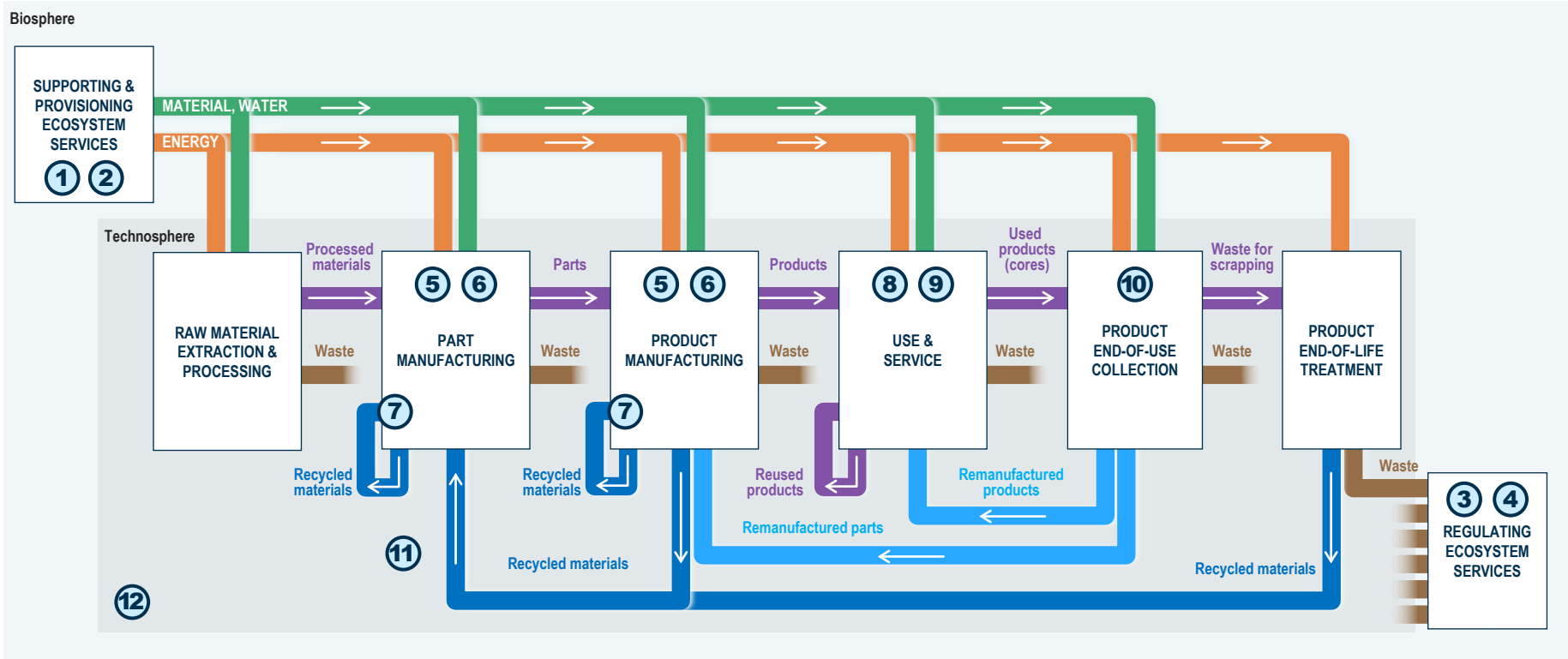
## Principle 11. Develop circular processes

→ develop materials, processes and systems for minimum material heterogeneity and contamination to enable value recovery

## Principle 12. Maximise value delivery through eco-efficient products

→ design and operate processes and systems for maximum value to society per unit of resource consumed; dematerialisation, miniaturisation, multi-functionality, modularisation, upgradability, reparability, durability, servitization, etc.

# Mapping the regenerative principles



# Measuring regenerative sustainability

Global

Regional

Local

	Air	Water	Land	Resources
	<p>▼ <b>Climate change</b> Emissions of CO<sub>2</sub> contributing to atmospheric concentration</p> <p>▲ <b>Climate action</b> Carbon offsetting and capture</p>	<p>▼ <b>Ocean acidification</b> Average surface ocean saturation state with respect to aragonite (carbonate ion concentration)</p>		
		<p>✘ <b>Change in biosphere integrity</b> <i>Genetic diversity</i>: Extinction rate, <i>Functional diversity</i>: Biodiversity Intactness Index</p>		
	<p>▼ <b>Stratospheric ozone depletion</b> Emissions of ozone-depleting substances contributing to stratospheric ozone concentration</p>	<p>▼ <b>Biogeochemical flows</b> Industrial and intentional biological fixation of Nitrogen (N) Phosphorus (P) flow from freshwater systems into the ocean Phosphorus flow from fertilizers to erodible (agricultural) soils</p>		<p>▼ <b>Fossil resource use</b> Abiotic resource depletion</p>
	<p>▼ <b>Photochemical ozone formation</b> Nitrogen oxides, carbon monoxide and volatile organic compounds contributing to tropospheric ozone concentration</p>	<p>▼ <b>Marine eutrophication</b> Fraction of nutrients reaching marine end compartment (N)</p>	<p>▼ <b>Terrestrial eutrophication</b> N deposition acidifying soils and altering land productivity</p>	<p>▼ <b>Mineral and metal resource use</b> Abiotic resource depletion</p>
	<p>▼ <b>Atmospheric aerosol loading</b> Emissions of aerosol particles (particulate matter, pollutants, smoke)</p>	<p>▼ <b>Freshwater eutrophication</b> Fraction of nutrients reaching freshwater end compartment (P)</p>		<p>✘ <b>Sustainable sourcing</b> Shift to renewables without exceeding renewal rates to conserve minerals and non-renewable resources</p>
	<p>▼ <b>Introduction of novel entities</b> Chemical pollution from persistent organic pollutants (e.g. CFC)</p>	<p>▼ <b>Freshwater use</b> Consumptive blue water use/withdrawal as % of mean monthly river flow</p>	<p>✘ <b>Land-system change</b> Area of forested land as % of original forest cover and as % of potential forest</p>	<p>✘ <b>Life cycle circularity</b> Recovery potential through reuse, remanufacturing and recycling</p>
	<p>▼ <b>Particulate matter, human toxicity</b> Impact on human health</p>	<p>▼ <b>Ecotoxicity, freshwater</b> Comparative Toxic Unit for ecosystems</p>	<p>▼ <b>Land use and degradation</b> Soil erosion, loss of nutrient-rich topsoil</p>	<p>✘ <b>Resource circularity</b> Consumption of renewables, recovered parts and recycled materials</p>
	<p>▲ <b>Air quality rehabilitation</b> Treatment and removal of airborne pollutants through pollution control technology (e.g. scrubber, catalytic converter, thermal oxidizer)</p>	<p>▼ <b>Water use</b> User deprivation potential</p>	<p>✘ <b>Landscape structure</b> Industrial activities integration in the biophysical environment</p>	<p>✘ <b>Industrial symbiosis</b> Exchange of waste and by-products between industrial actors</p>
		<p>▲ <b>Water quality rehabilitation</b> Water amendments (recapture or dilute contaminants to healthy composition)</p>	<p>▲ <b>Landscape rehabilitation</b> Decontamination and redevelopment</p>	<p>✘ <b>Resource efficiency</b> Energy, material and water usage</p>
	<p>✘ <b>Acceptable anthropogenic noises and disturbances</b> Considerations for sensitivity thresholds of natural habitats to operate well within them</p>			
				<p>✘ <b>Local circularity</b> On-site recirculation of resource and wastes (energy, water and material)</p>

## Annotations

- ▼ Reduce negative impact
- ▲ Create positive impact
- ✘ Both/potential for positive impact

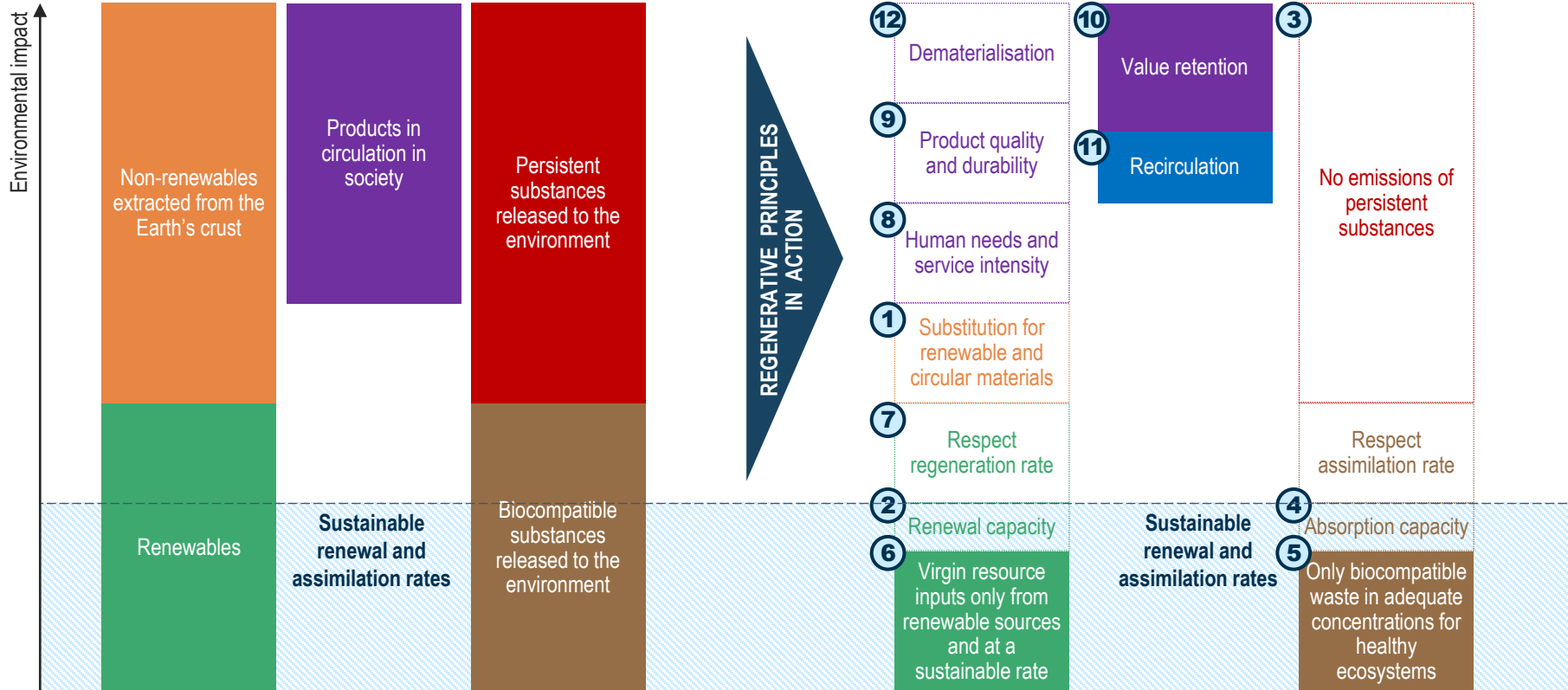
**Earth-system process** – Global and regional control variables from the Planetary Boundaries [26]

**Environmental footprint monitoring** – Impacts and indicators from the European Commission [27]

**Environmental performance betterment** – Actions for eco-efficiency, circularity and regenerative sustainability

[see *Reference list* in the paper]

# Reducing environmental impacts below the regenerative threshold



# With thanks to my team, colleagues, project partners and students for advancing the field of industrial sustainability! Yes, we can! 😊



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