Implementing Sustainable Manufacturing:

Recent Progress, Challenges and Opportunities

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UK UNIVERSITY OF KENTUCKY College of Engineering

ISM Institute for Sustainable Manufacturing

Sustainable Manufacturing: Definitions

- ***Numerous definitions*** and descriptions exist for sustainable manufacturing:

- US Department of Commerce, 2009
- NACFAM, 2009
- NIST, 2010
- US-EPA, 2012
- ASME, 2011, 2013
- NSF 2013
- ISM, 2014

- Sustainable manufacturing offers a new way of ***producing functionally superior products using innovative sustainable technologies and manufacturing methods*** through the coordination of capabilities ***across the entire supply chain, not just the process chain***

- Sustainable manufacturing must enable ***sustainable value creation for all stakeholders.***

Sustainable Manufacturing: Revised Definition

Sustainable manufacturing at ***product, process and systems*** levels must:

- demonstrate reduced ***negative environmental impact,***
- offer improved ***energy and resource efficiency,***
- generate ***minimum quantity of wastes***,
- provide ***operational safety,*** and
- offer improved ***personnel health***

while maintaining and/or improving the ***product and process quality*** with the overall ***life-cycle cost benefits.***

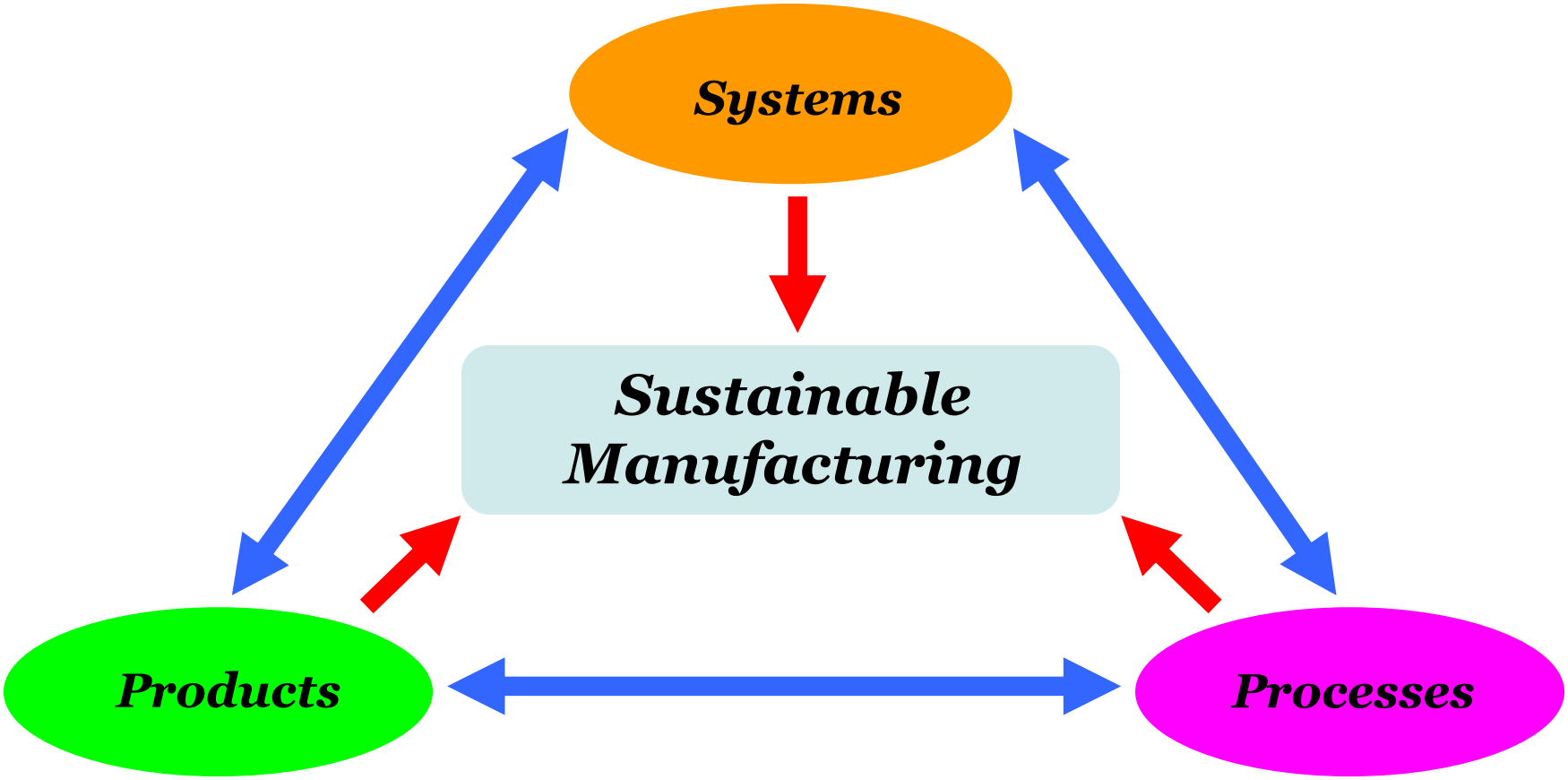
Source: Jawahir et al. (2014) and Jayal et al. (2010) – Adapted from US Department of Commerce (2009)

Sustainable Manufacturing: Basic Elements

Expectations:

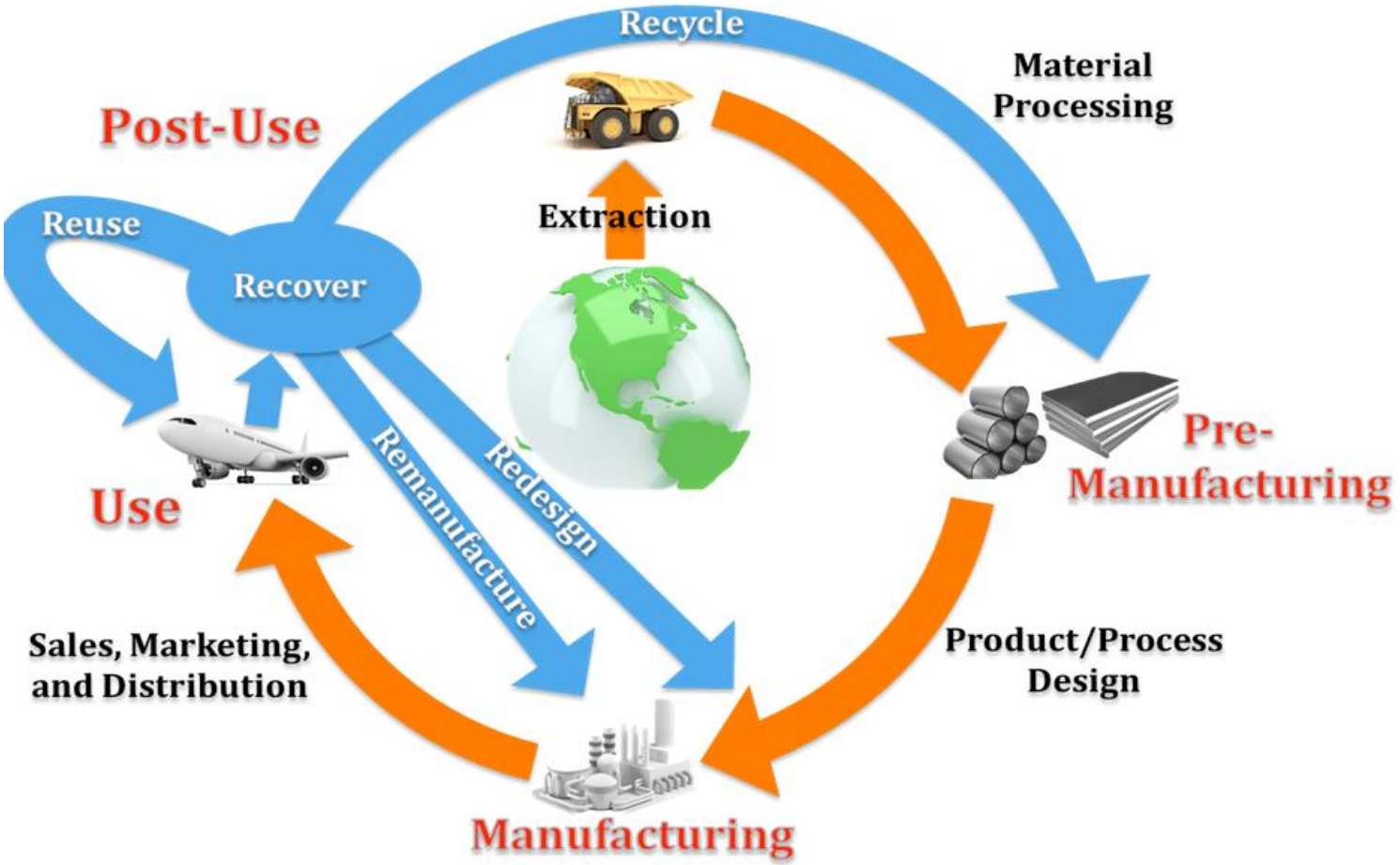
- Reducing ***energy consumption***
- Reducing ***waste***
- Reducing ***material utilization***
- Enhancing ***product durability***
- Increasing ***operational safety***
- Reducing ***toxic dispersion***
- Reducing ***health hazards/Improving health conditions***
- Consistently improving ***manufacturing quality***
- Improving ***recycling, reuse and remanufacturing***
- Maximizing ***sustainable sources of renewable energy***

Integral Elements of Sustainable Manufacturing



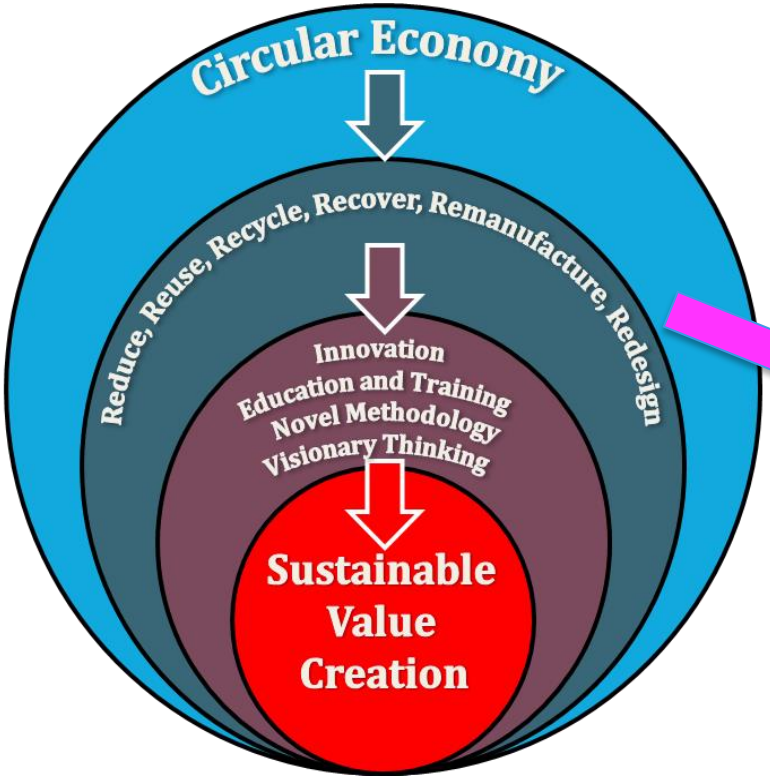

Recycle
Material Processing
Post-Use
Extraction
Reuse
Recover
Redesign
Remanufacture
Use
Pre-Manufacturing
Sales, Marketing, and Distribution
Product/Process Design
Manufacturing

Product Recovery as a Starting Point for Multi Life-cycle Products

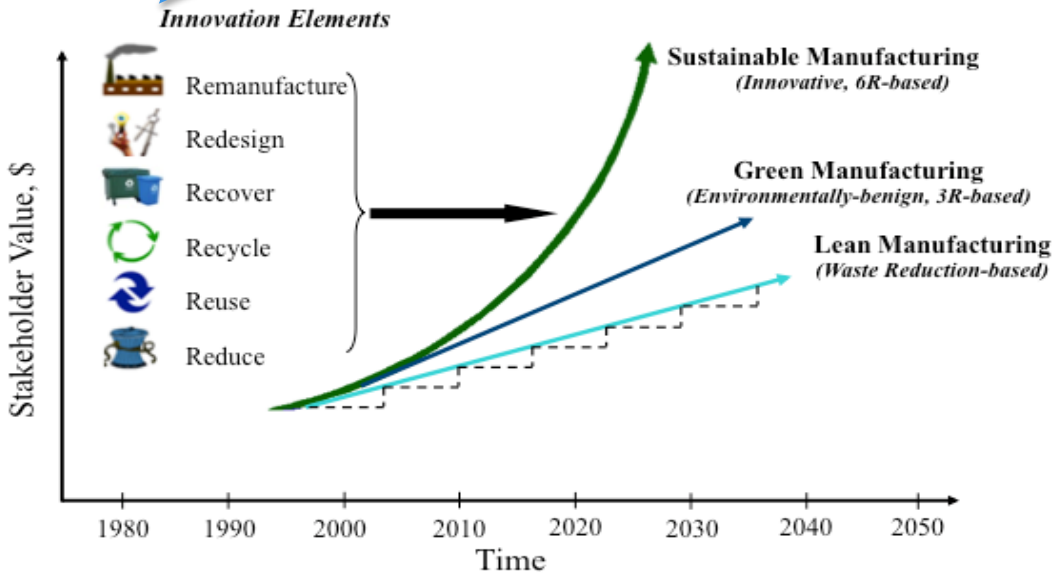


Source: Jawahir and Bradley (2015)

From Circular Economy to Sustainable Value Creation

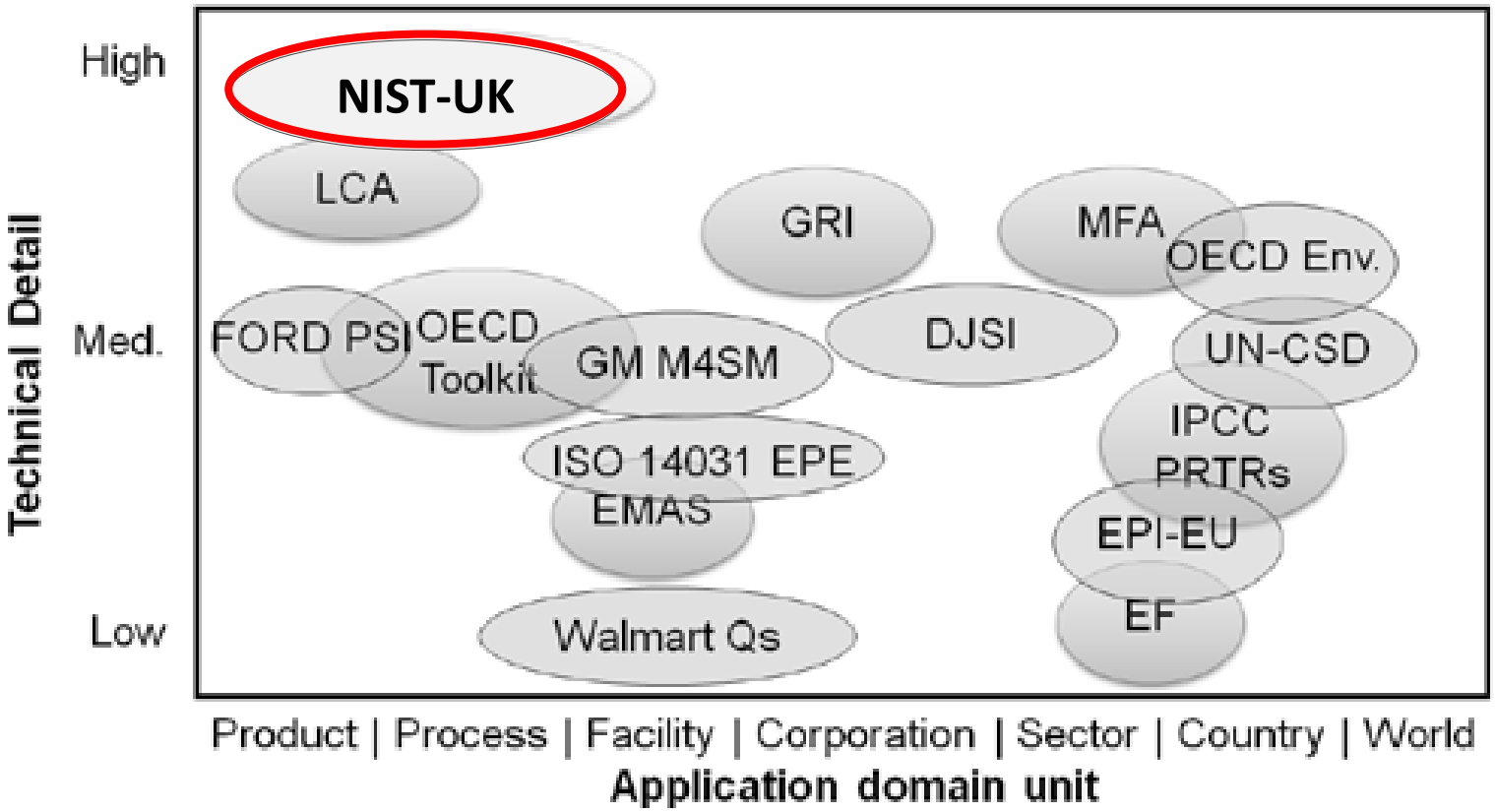


From Lean to Green to Sustainable Manufacturing



Source: Jawahir and Bradley (2015)

Comparison of the existing measurement systems



Source: Feng et al. (2010)

Product and Process Metrics for Sustainable Manufacturing: NIST-sponsored Project (2010-14)

Project Title: Development of Metrics and Framework for Products and Processes in Sustainable Manufacturing

Project Team:

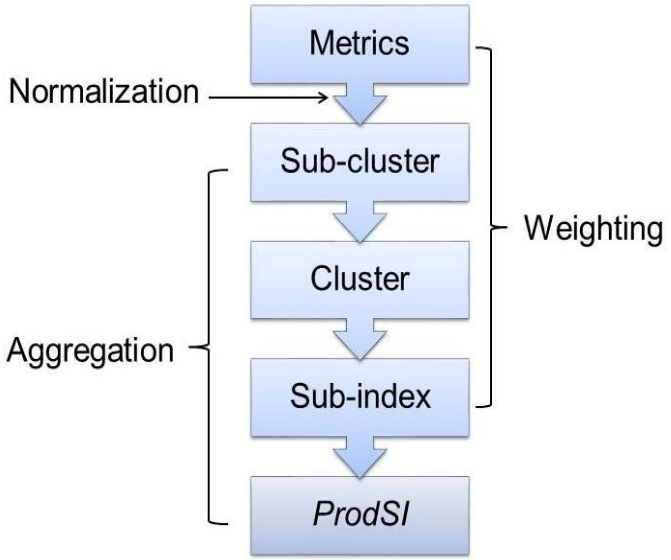
Faculty: Dr. I.S. Jawahir, Dr. F. Badurdeen, Dr. O.W. Dillon, Dr. K. Rouch
Graduate Students: T. Lu, M. Shuaib, X. Zhang, A. Huang, C. Stovall

Sponsor: NIST ***Industry partners:*** TOYOTA GE LEXMARK

Project Objective:

To develop and implement tools and principles for quantitative evaluation of manufactured products and their manufacturing processes from the aspect of sustainable manufacturing

Product Sustainability Clusters

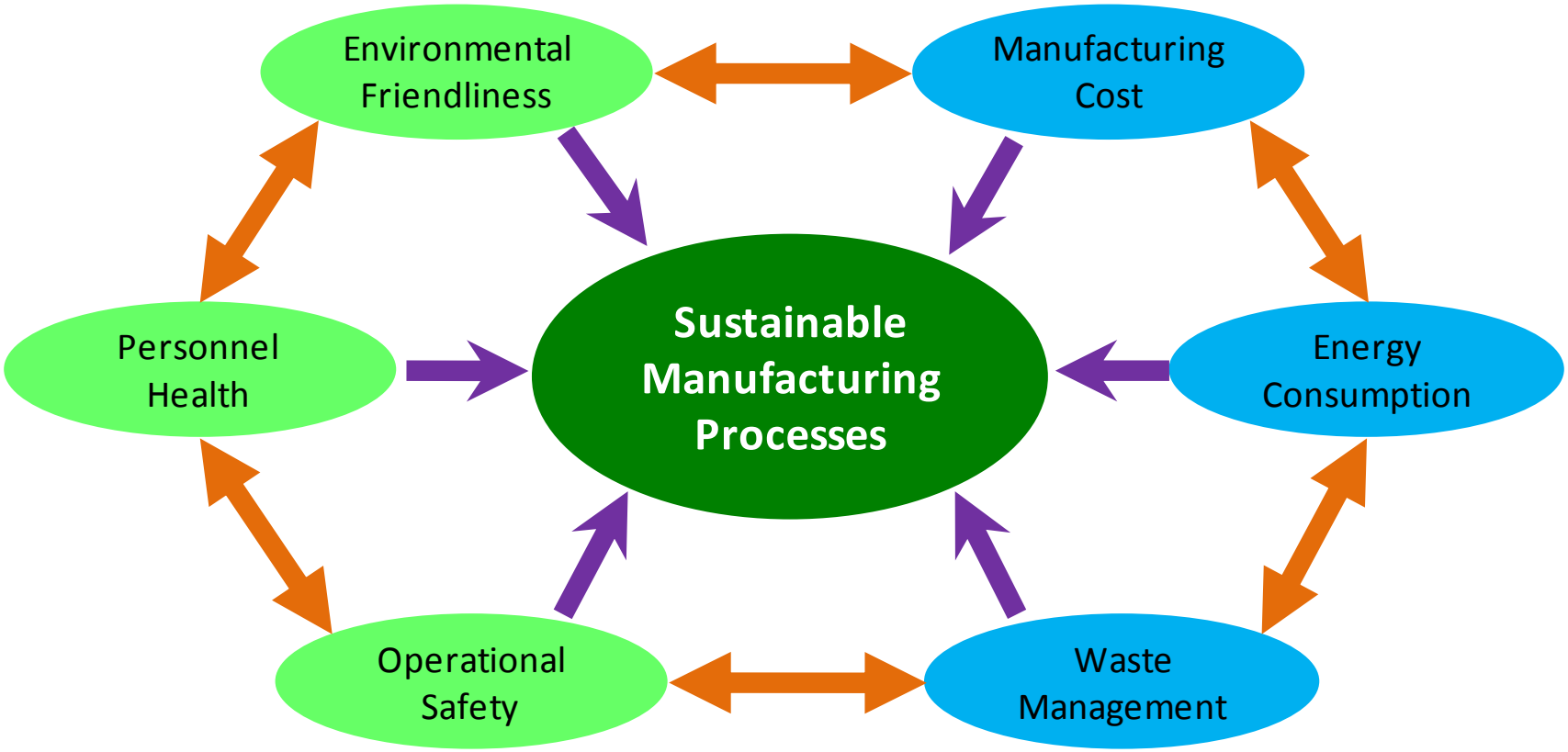


Source: Hapuwatte et al. (2016)

Example Metrics for Product Clusters and Life-cycle Stages

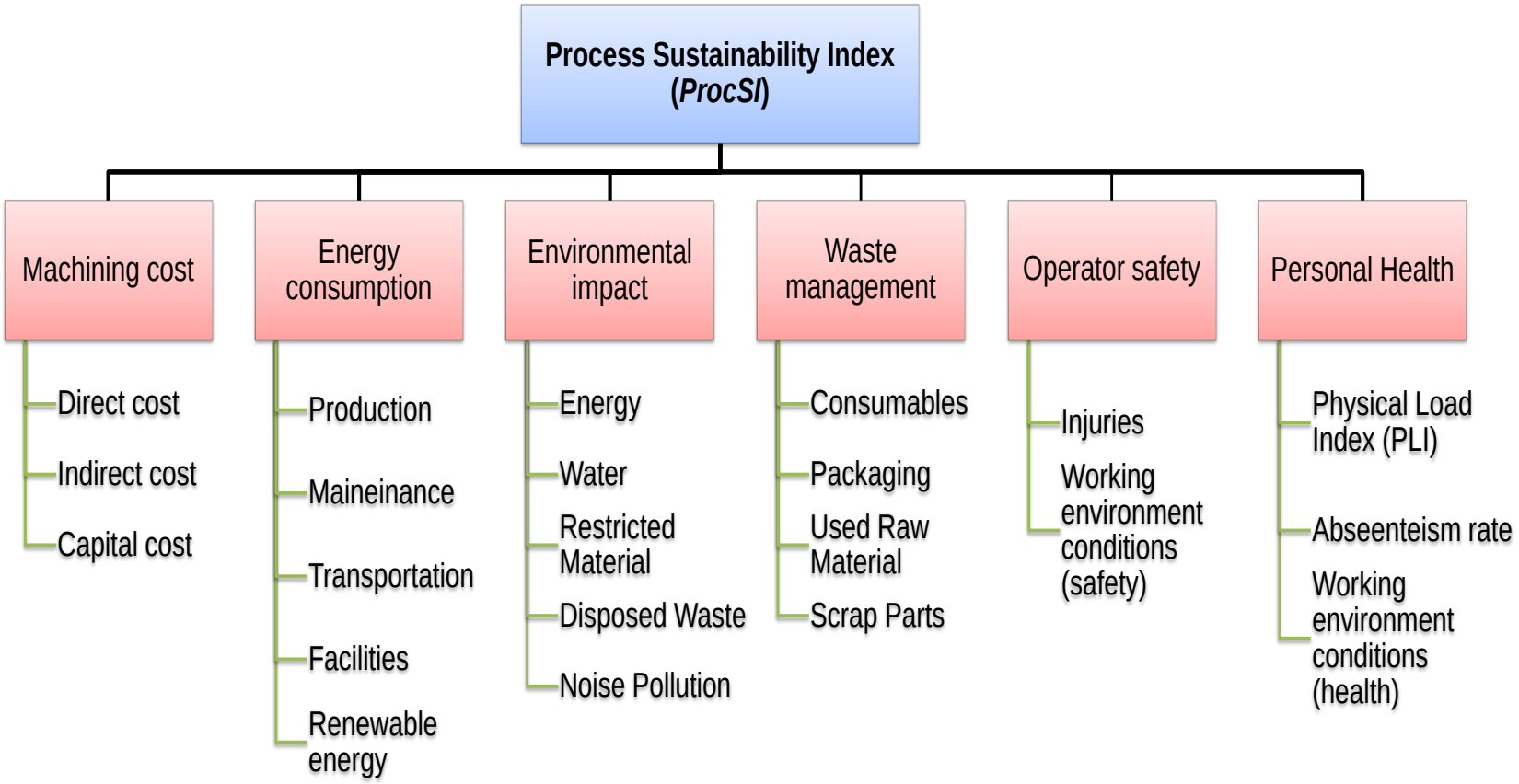
Metrics Clusters	Example Metrics	Unit (D/L dimensionless)	PM (pre-mfg.)	M (mfg.)	U (use)	PU (post-use)
Residues	Emissions Rate (carbon-dioxide, sulphur-oxides, nitrous-oxides etc.)	mass/unit	√	√	√	√
Energy Use and Efficiency	Remanufactured Product Energy	kWh/unit		√	√	√
	Maintenance/ Repair Energy	kWh/unit			√	
Product End-of-Life Management	Design-for-Environment Expenditure	$/$ (D/L)		√		
Material Use and efficiency	Restricted Material Usage Rate	mass/unit	√	√		√
Water Use and Efficiency	Recycled Water Usage Rate	gallons/unit	√	√		√
Cost	Product Operational Cost	$/unit			√	
Innovation	Average Disassembly Cost	$/unit				√
Profitability	Profit	$/unit		√		
Product Quality	Defective Products Loss	$/unit		√		
	Warranty Cost Ratio	$/unit			√	
Education	Employee Training	Hours/unit	√	√		√
Customer Satisfaction	Repeat Customer Ratio	(D/L)		√	√	
	Post-Sale Service Effectiveness	(D/L)			√	
Product End-of-Life Management	Ease of Sustainable Product Disposal	$/unit			√	
Product Safety and Societal Well-being	Product Processing Injury Rate	incidents/unit	√	√		√
	Landfill Reduction	mass/unit	√	√	√	√

Process Sustainability Elements



Source: Wanigarathne et al. (2004)

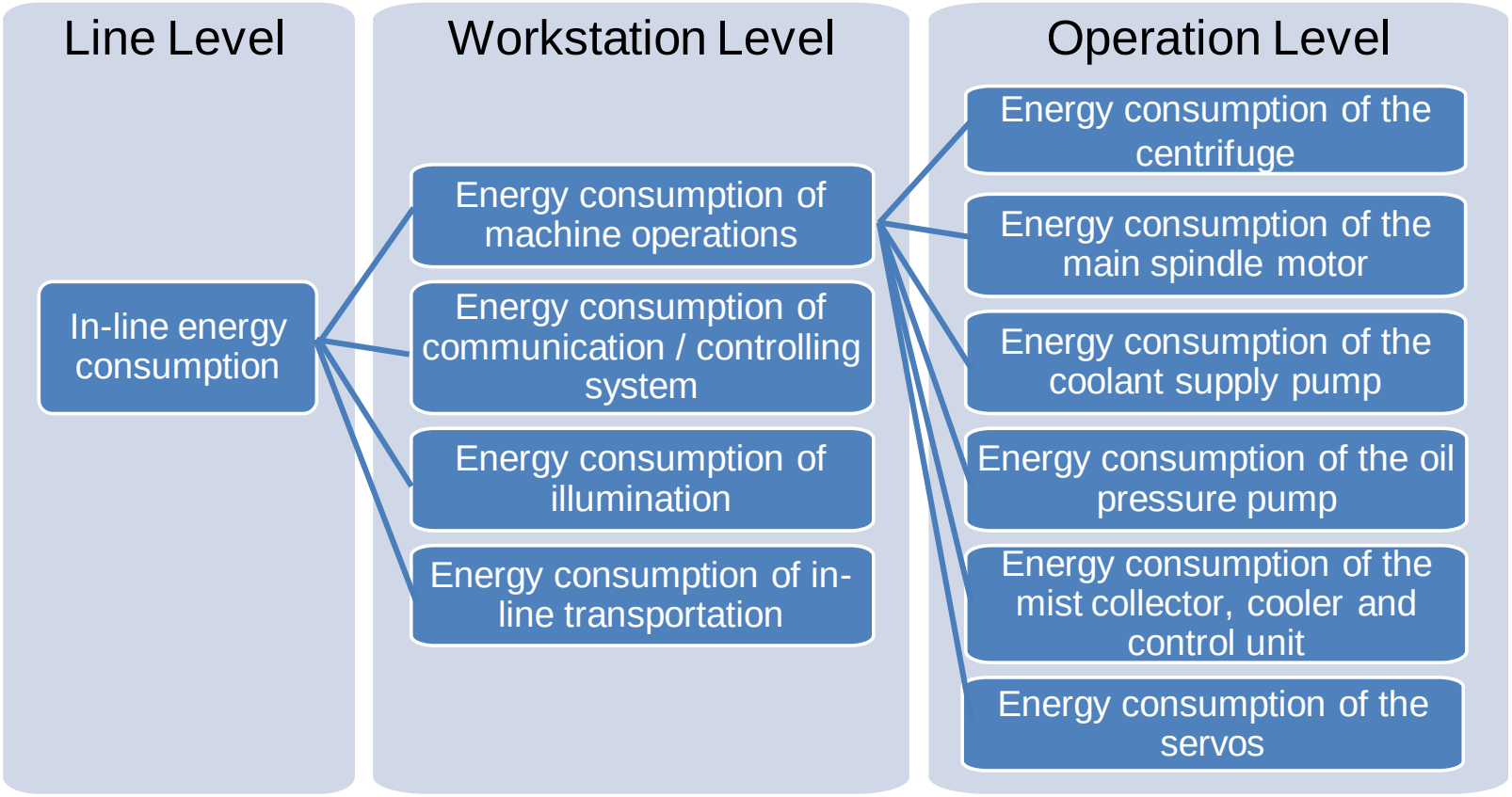
Process Sustainability Clusters and Sub-clusters



Process Sustainability Metrics

Environmental Impact	Energy Consumption	Cost
GHG emission from energy consumption of the line (ton CO_2 eq./unit)	In-line energy consumption (kWh/unit)	Labor cost ($/unit)
Ratio of renewable energy used (%)	Energy consumption on maintaining facility environment (kWh/unit)	Cost for use of energy ($/unit)
Total water consumption (ton/unit)	Energy consumption on transportation into/out of the line (kWh/unit)	Cost of consumables ($/unit)
Mass of restricted disposals (kg/unit)	Ratio of use of renewable energy (%)	Maintenance cost ($/unit)
Noise level outside the factory (dB)		Cost of by-product treatment ($/unit)
		Indirect labor cost ($/unit)
Operator Safety	**Personnel Health**	**Waste Management**
Exposure to Corrosive/toxic chemicals (points/person)	Chemical contamination of working environment (mg/m^3)	Mass of disposed consumables (kg/unit)
Exposure to high energy components (points/person)	Mist/dust level (mg/m^3)	Consumables reuse ratio (%)
Injury rate (injuries/unit)	Noise level (dB)	Mass of mist generation (kg/unit)
	Physical load index (dimensionless)	Mass of disposed chips and scraps (kg/unit)
	Health related absenteeism rate (%)	Ratio of recycled chips and scraps (%)

Three-level Process Sustainability Metrics for Energy Consumption



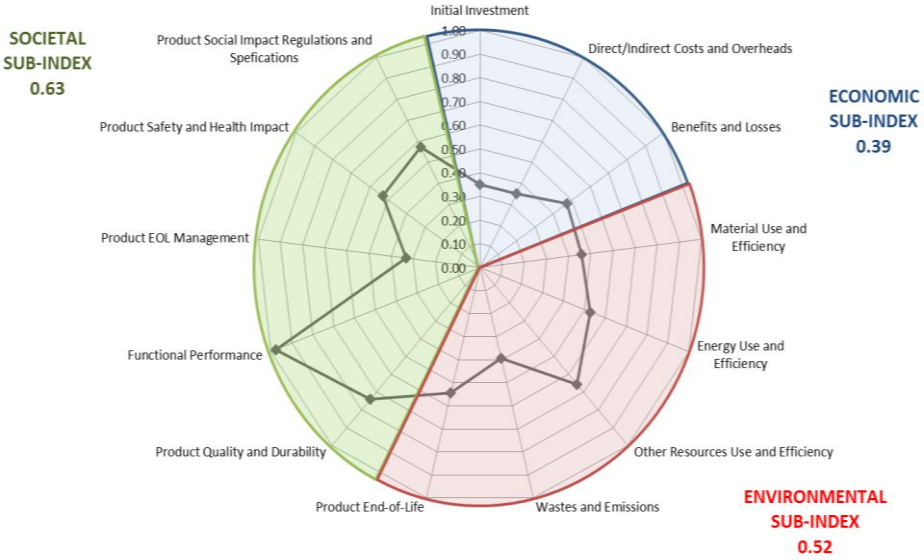
ProdSI and ProcSI Evaluation

$$ProdSI = \frac{1}{3}\left(Ec + Ev + So\right) = \frac{1}{3}\left(\sum_{i=1}^{3} w_i^c C_i + \sum_{i=4}^{8} w_i^c C_i + \sum_{i=9}^{13} w_i^c C_i\right) \quad C_m = \sum SC_j w_j^{sc} \;\forall\, j \quad SC_n = \sum M_k w_k^m \;\forall\, j$$

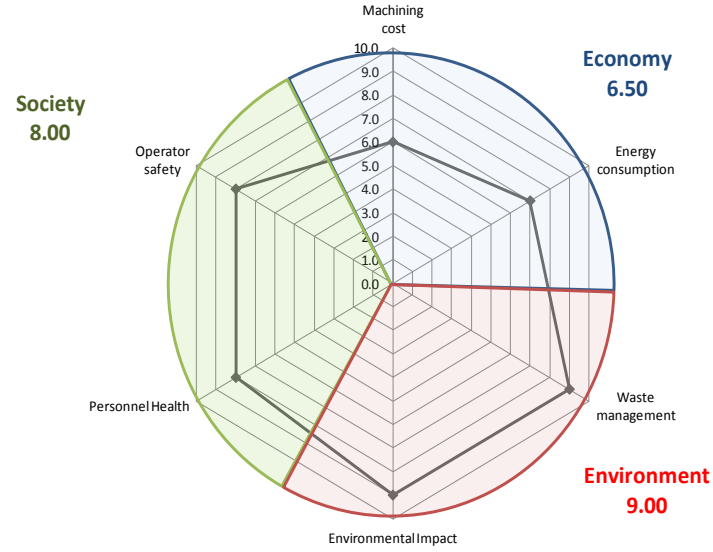
$$ProcSI = \frac{1}{6}\sum_{i=1}^{6} C_i = \frac{1}{6}\left(C_1 + C_2 + \frac{1}{5}\sum_{i=10}^{14} w_i^{sc} SC_i + \frac{1}{4}\sum_{i=15}^{18} w_i^{sc} SC_i + \frac{1}{3}\sum_{i=19}^{21} w_i^{sc} SC_i + \frac{1}{2}\sum_{i=22}^{23} w_i^{sc} SC_i\right)$$

$$SC_n = \sum w_j^m M_j \;\forall\, j$$

Examples of ProdSI and ProcSI



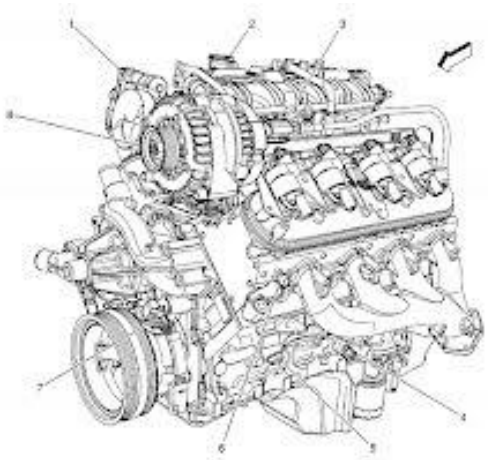
(a) *ProdSI*



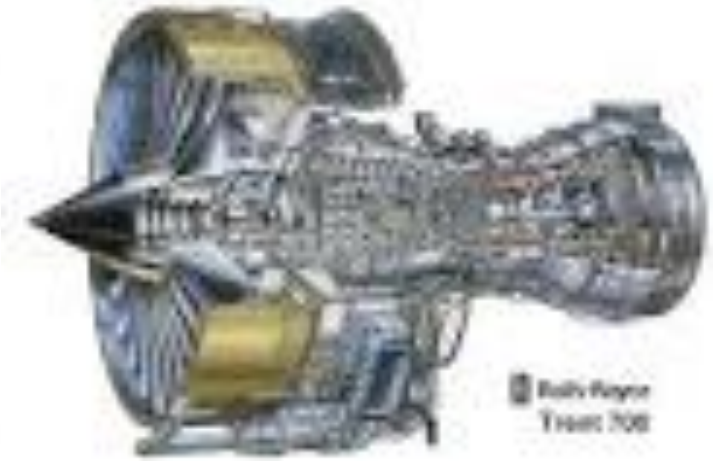
(b) *ProcSI*

Sustainability Improvement in Products and Processes

Case studies were conducted on three major manufactured products

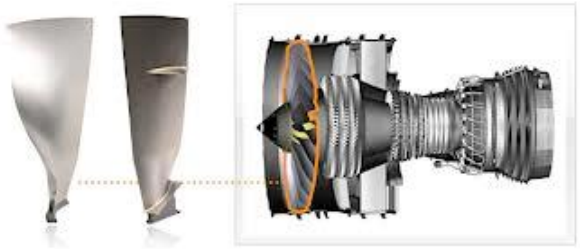


Automotive Product

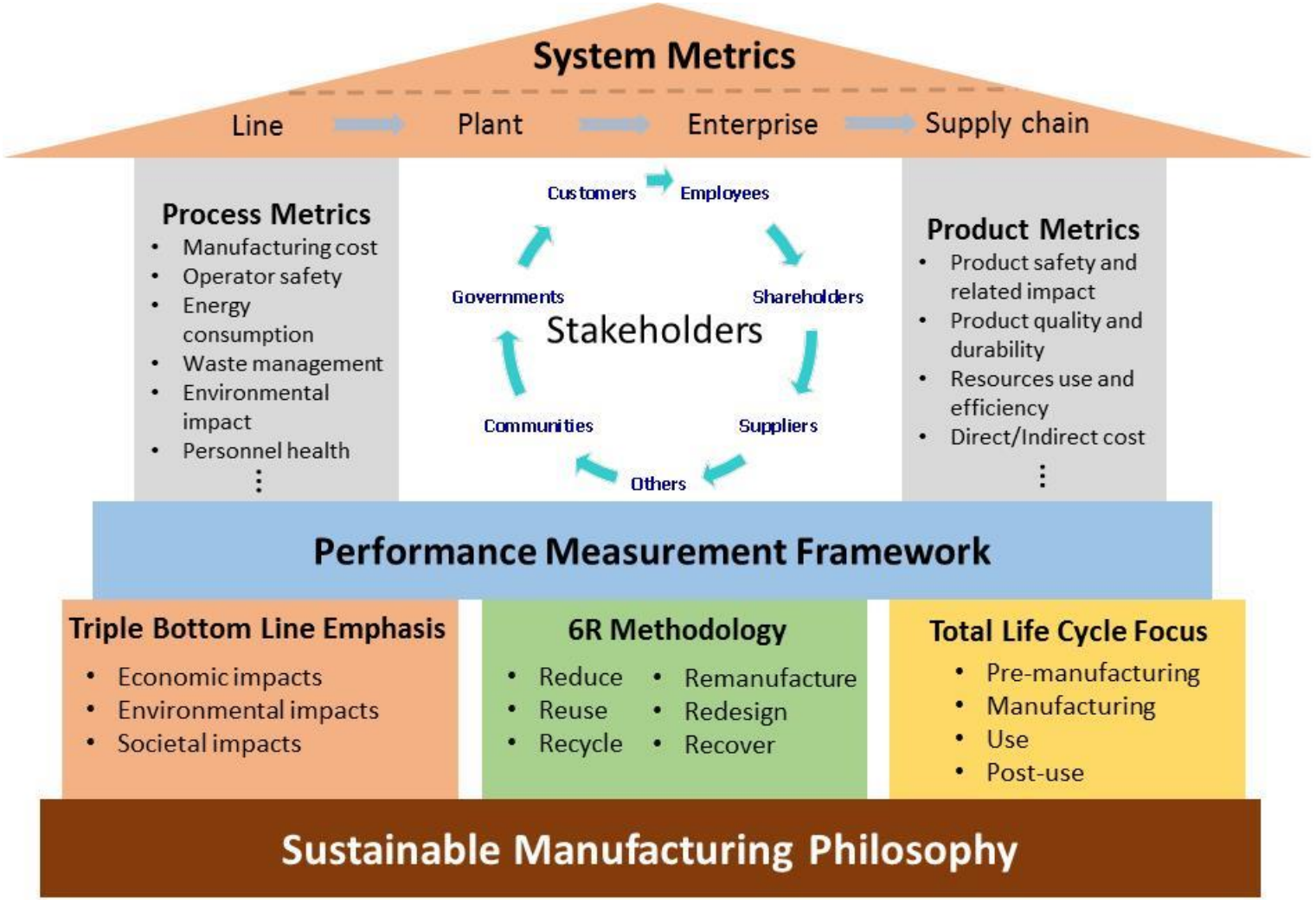


Aerospace Product

Consumer Product

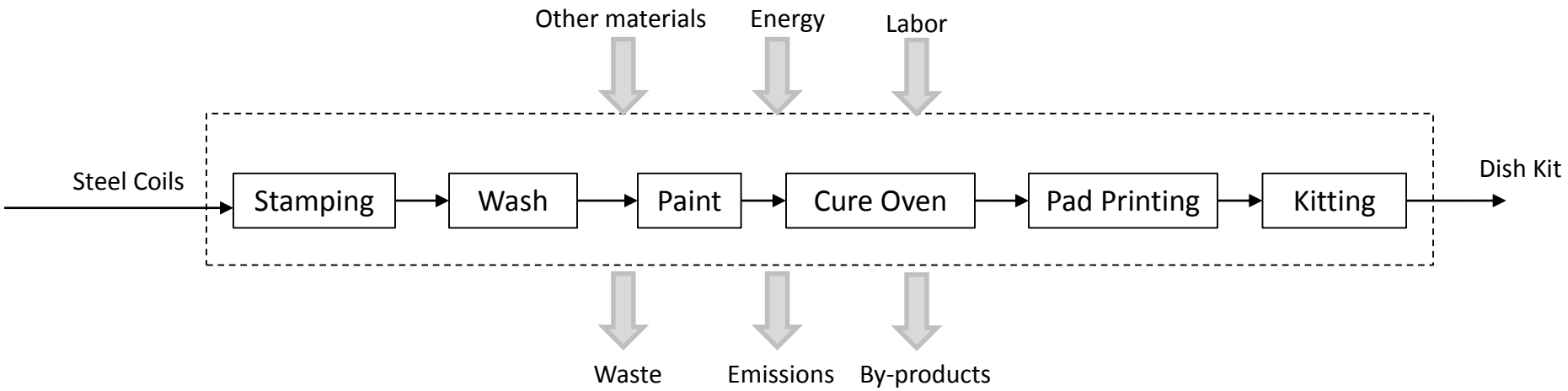


Metrics Hierarchy – Products/Processes/Systems



System Metrics – Production Line Level

Production line: Example: Satellite Dish Production Line



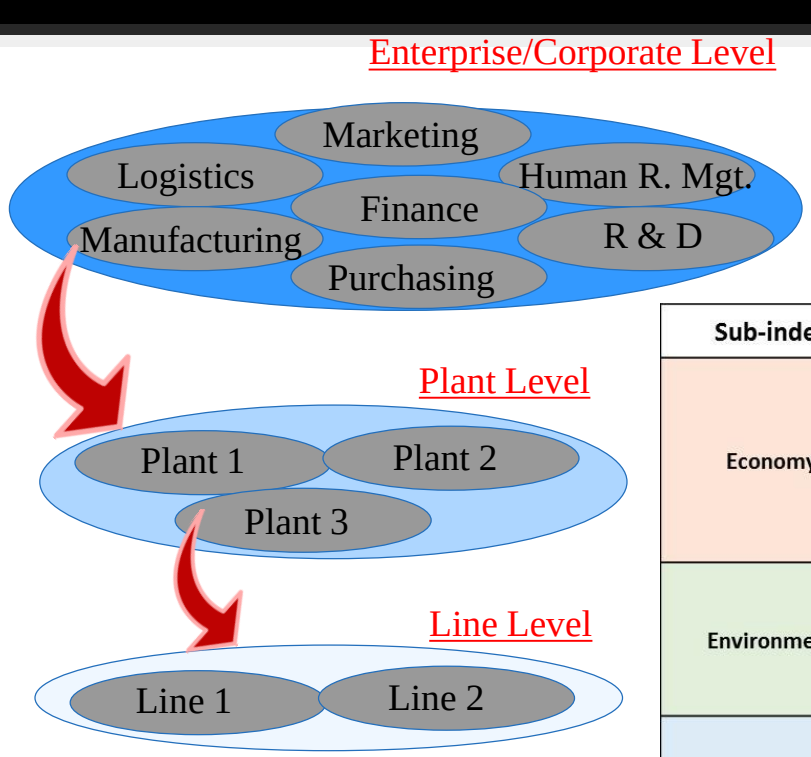
Line-level Sustainability Evaluation

Economic Sustainability Evaluation	Cycle time
	Changeover time
	Uptime
	Inventory

Environmental Sustainability Evaluation	Raw material usage
	Process water consumption
	Process energy consumption
	Transportation energy consumption

Societal Sustainability Evaluation	Physical Load Index (PLI)
	Noise
	Risk Circle

Systems Metrics – Enterprise Level



Sub-index	Clusters	Sample metrics
Economy	Internal business process	Indirect cost ratio Cash flow margin
	Financial perspective	Return on capital employed Financial robustness
	Customer perspective	Order fill rate On-time delivery ratio
	Learning & growth	Recovery cost Cost of recycling
Environment	Residues	GHG emission rate Solid emission rate
	Energy	Energy efficiency rate Renewable energy ratio
	Resource (other than energy)	Restricted raw material usage Water usage rate
Society	Anti-corruption	Anti-competitive behavior index Employee awareness on anti-competitive behavior
	Supplier development and training/practices	Supplier compliance index supplier training intensity index
	Employee development and trainning	Employee training intensity index Employee reward ratio
	Customer satisfaction/awareness	Repeat customer ratio Product customization ratio
	Community development	Local community hiring ratio Community contribution ratio
	Diversity and equal opportunity	Diversity ratio Employees conflict ratio
	Compliance and product responsibility	Product compliance ratio Compliance incidence rate

Implementing Product and Process Sustainability Metrics

Limitations:

- **Slow progress and limited effectiveness** in implementing sustainable practices --- Lack of economic benefit studies, standards, or best practices
- **No comprehensive tools and techniques** for total life-cycle evaluation
- **Complexity in measuring and quantifying sustainability** in products and processes, and greater difficulty in evaluating at system/enterprise level

Outlook and Opportunities:

- **Metrics-based sustainability evaluation** of products, processes and systems offers an new opportunity for implementation in manufacturing
- **Innovative methods for achieving improved resource efficiency** (energy, materials, water, etc.) and end-of-life (EOL) management
- **Improved manufacturing productivity** and **greater economic returns** through **sustainable value creation for all stakeholders**