Assessment of Product and Process Sustainability: *Towards Developing Metrics for Sustainable Manufacturing*

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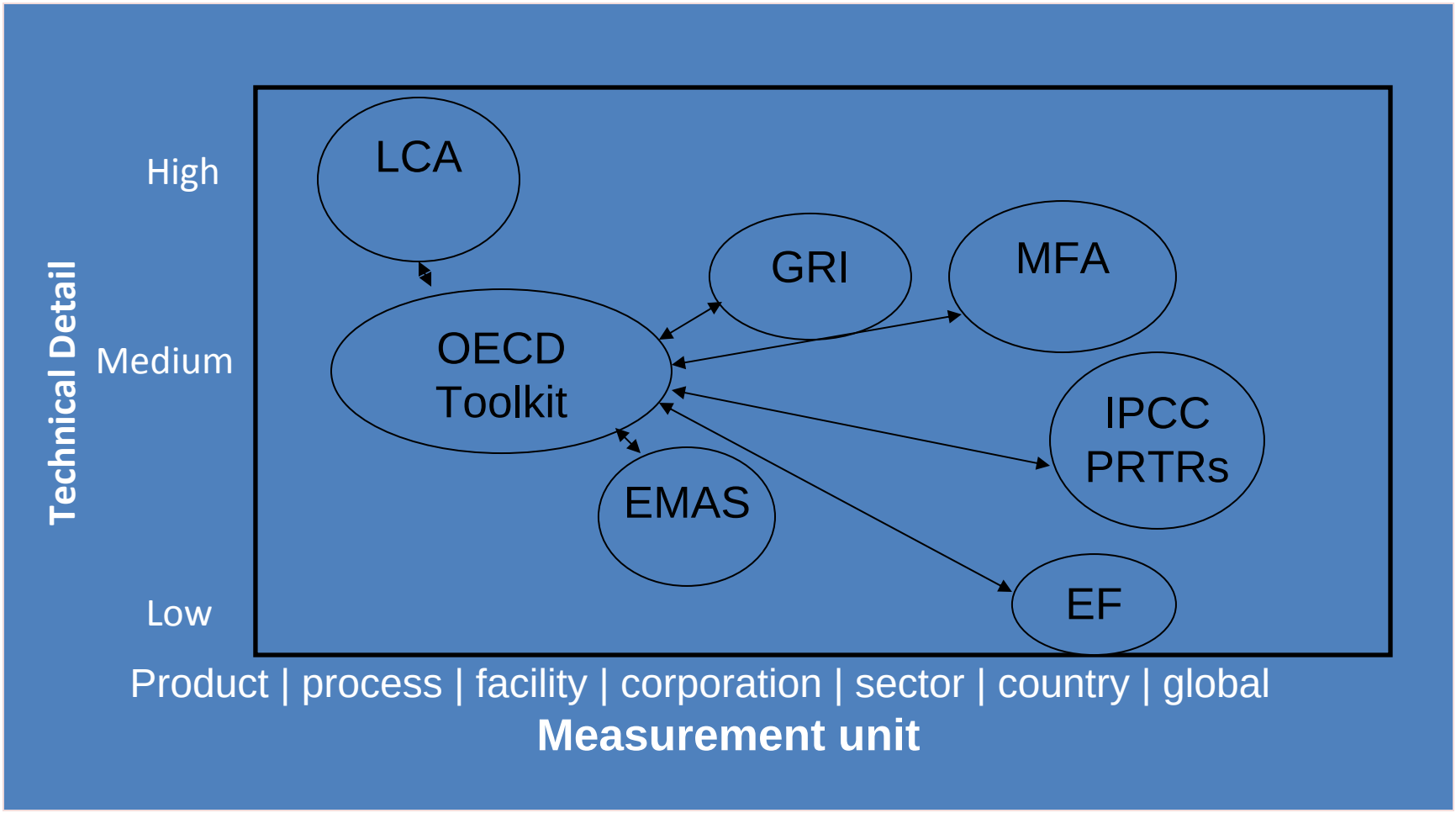
Presentation Outline

- General Background and Clarification on Metrics for Sustainable Manufacturing
- Product Sustainability Evaluation
- Process Sustainability Evaluation (Case Study: Machining)
- Summary of Current Efforts on Metrics Development at Product, Process, Enterprise and Supply Chain levels at the University of Kentucky
- Conclusions

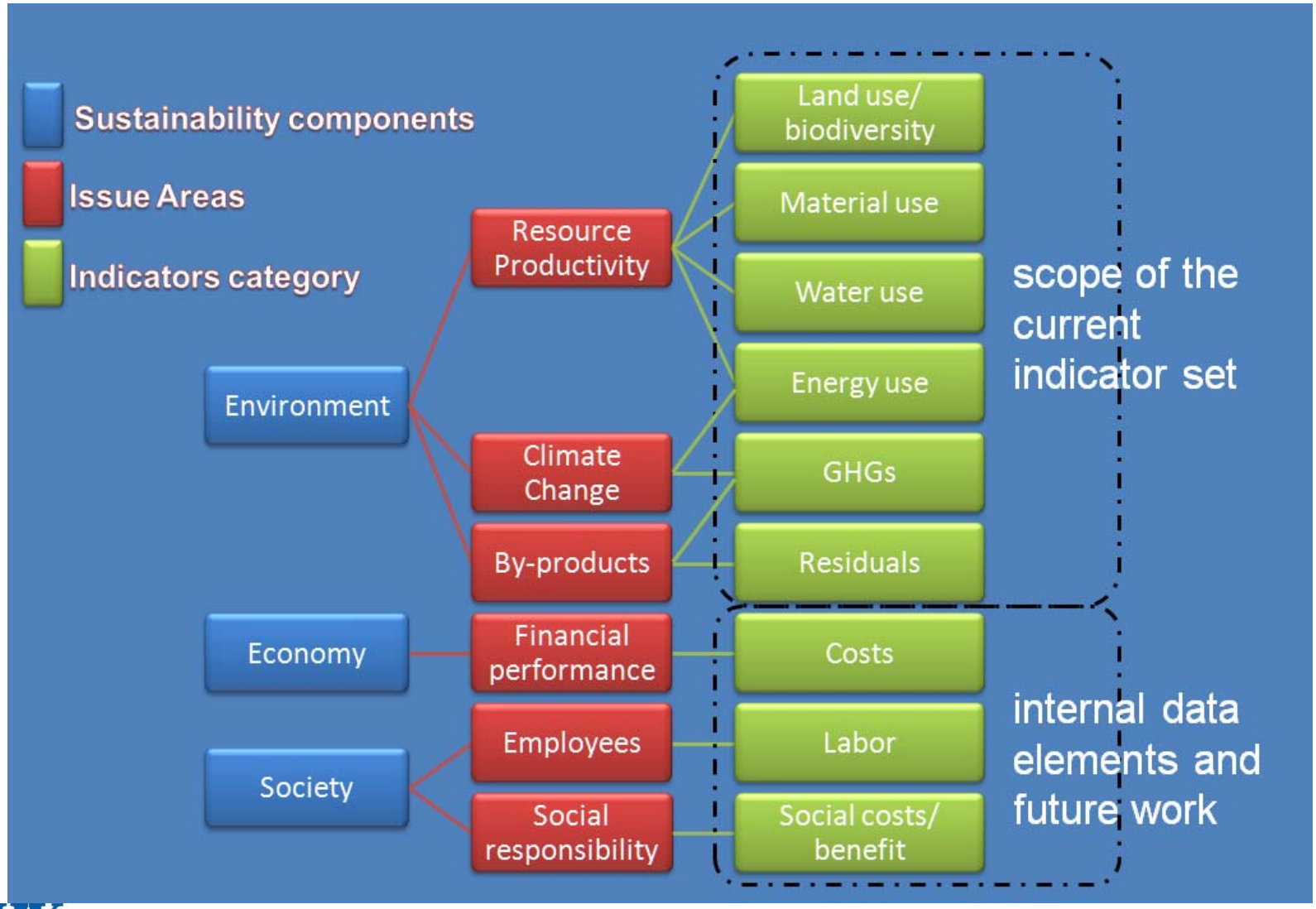
Metrics for Sustainable Manufacturing: *Some Clarifications*

- Sustainable manufacturing IS NOT just ***manufacturing processes*** or the resulting ***manufactured products***
- A ***multi-level*** approach is needed: ***products, processes, enterprise*** and ***supply chain*** levels need to be considered, with ***metrics*** identified ***for each level***
- ***Complex interactions*** among the various metrics need to be ***identified, characterized, measured and modeled for predictability*** of "sustainability content" for a manufactured product, manufacturing process, manufacturing enterprise, and the entire supply chain
- The ***science-base*** for sustainable manufacturing can be built only on a strong and meaningful framework for metric development at all levels
- ***Model-based metrics*** for sustainable manufacturing at all levels will serve as the ***driver for innovation, business growth, environmental protection and societal wellbeing***

Existing Metrics Approaches (Michael Bordt, OECD, 2009)



Indicator Categories (Michael Bordt, OECD, 2009)



Core Indicators (Michael Bordt, OECD, 2009)

	Facility oriented indicators	Product oriented indicators
Land use/ biodiversity	A1. Percent of land area that is "natural"	
Materials use	B1. Recycled content of material B3. non-renewable material s intensity	D1. Recycled content D2. Recyclability D3. Renewable materials content D7. Non-renewable materials intensity
Water use	B4. Water intensity	
Energy use	B2. Renewable proportion of energy C2. Energy intensity	D5. Annual energy consumption
GHGs	C1. GHG intensity	D6. Annual GHG production
Residuals	C3. Residuals intensity(total) C4. Intensity of releases to air C5.Intensity of releases to water	D4. Restricted substances content

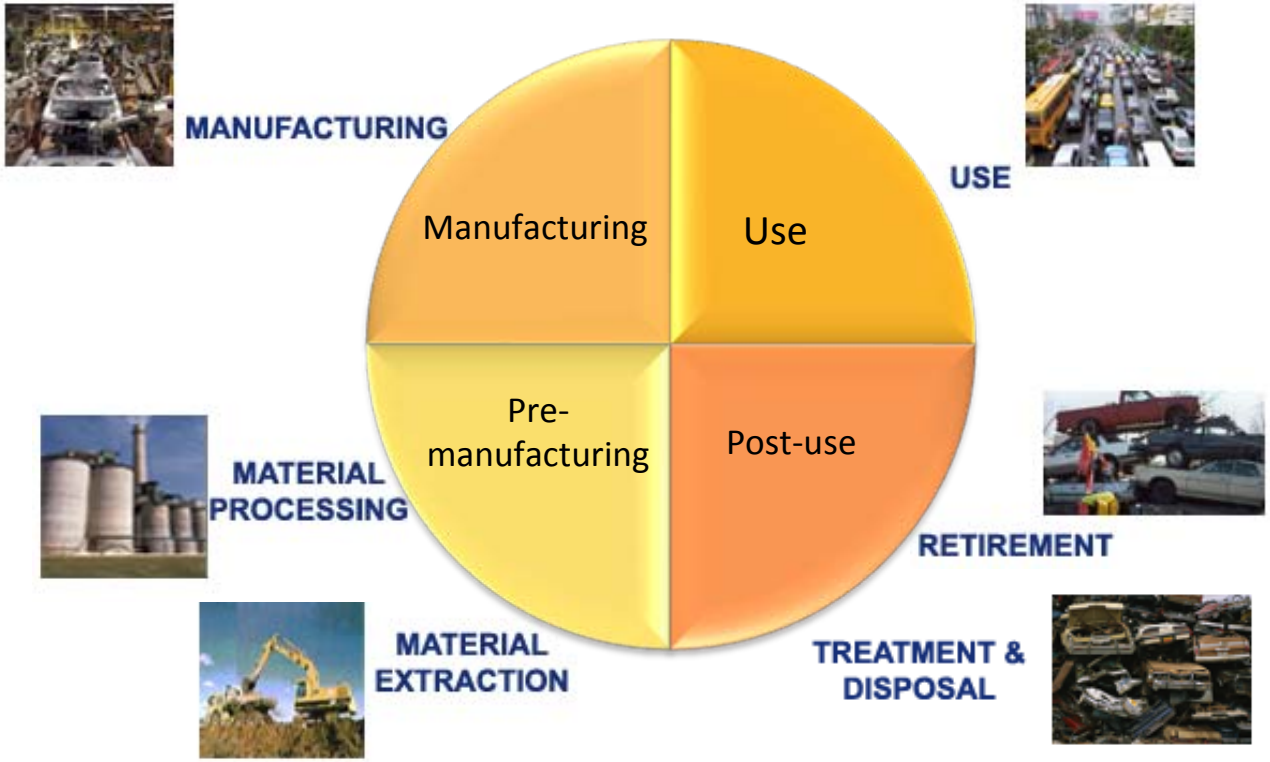
Early Attempt for Developing Product Sustainability Indicators

Economic	Environmental	Societal
Direct • Raw material cost • Labor cost • Capital cost	**Material Consumption** • Product & packaging mass • Useful product lifetime • Hazardous materials used	**Quality of Life** • Breadth of product availability • Knowledge or skill enhancement
Potentially Hidden • Recycling revenue • Product disposition cost	**Energy Consumption** • Life-cycle energy • Power use during operation	**Peace of Mind** • Perceived risk • Complaints
Contingent • Employee injury cost • Customer warranty cost	**Local Impacts** • Product recyclability • Impact upon local streams	**Illness & Disease Reduction** • Illnesses avoided • Mortality reduction
Relationship • Loss of goodwill due to customer concerns • Business interruption due to stakeholder interventions	**Regional Impacts** • Smog creation • Acid rain precursors • Biodiversity reduction	**Accident & Injury Reduction** • Lost time injuries • Reportable releases • Number of incidents
Externalities • Ecosystem productivity loss • Resource depletion	**Global Impacts** • CO_2 Emissions • Ozone depletion	**Health & Wellness** • Nutritional value provided • Food costs

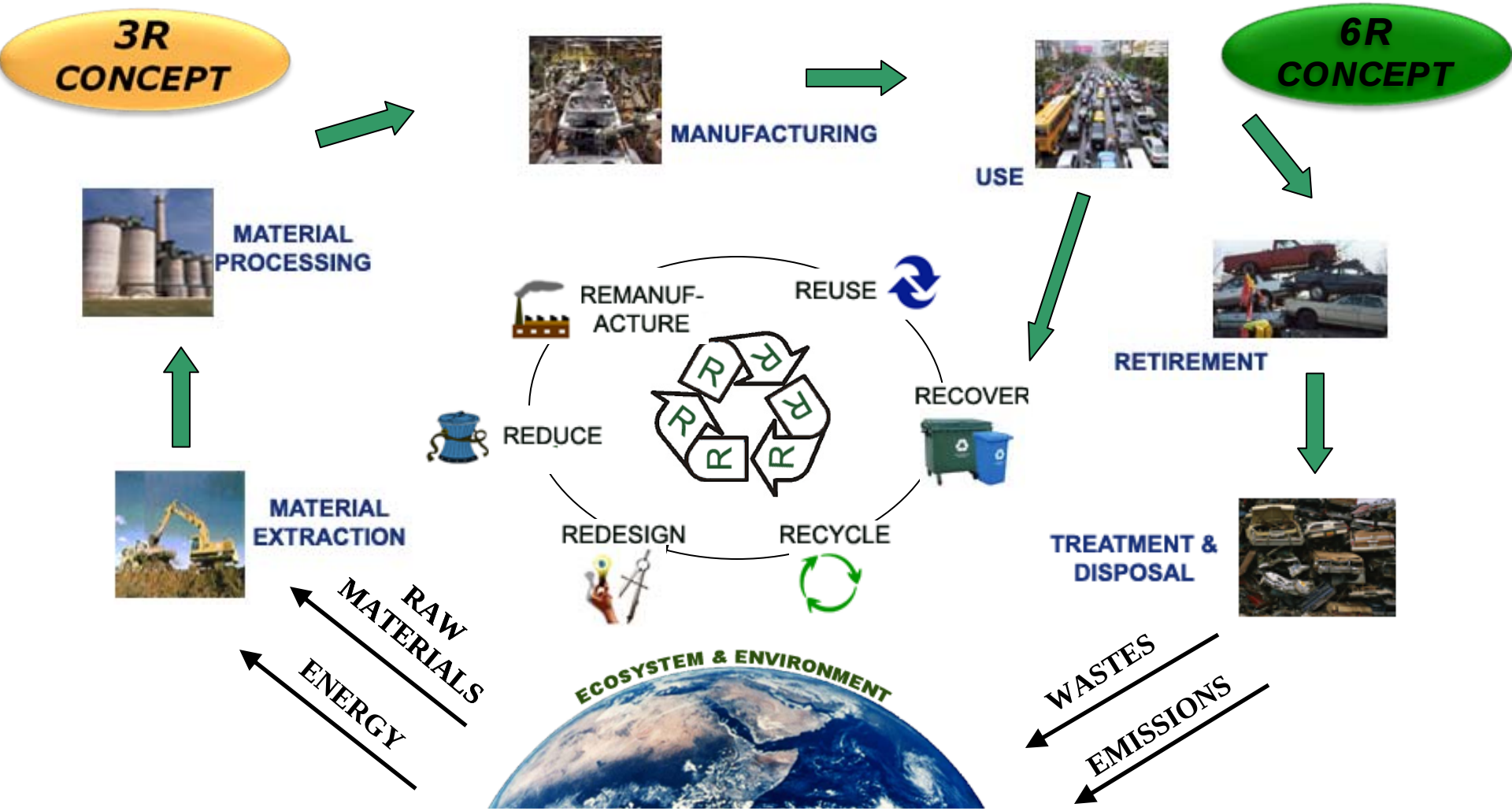
(Fiksel et al., 1998)

Holistic and Total Life-cycle Approach

Emphasis on all four product lifecycle stages



Closed-loop Material Flow – The 6R Approach



Source: Jawahir et al. (2006)

Elements and Sub-elements of Product Sustainability

(Jawahir et al., 2006)

Methodology for Calculating Product Sustainability Index (PSI)

A new 3 step methodology is introduced

Step 1:

- The product developers need to identify potential influencing factors based on national/international regulations, federal and state laws, to be important factors from their own perspective.
- Focus on all three components of sustainability.
- Focus on all four life-cycle stages.

Step 2:

- A 3x4 matrix that represents all components of sustainability and all four life-cycle stages.
- Allocate a score/rating between 0-10 for each influencing factor.
- Weighting can be applied to the influencing factors based importance.
- Non-quantifiable factors can be scored based on designers' experience and judgment.

Analytical Foundation of Product Design for Sustainability

Step 3:
Methodology for Calculating PSI

$$PSI_{(en_pm)} = \{[\sum_{i=1}^{n} IF_{(en_pm)_i}]/(n*10)\}*100\%$$

$PSI_{(en_pm)}$	=	Product Sustainability Index for Environment component of Pre-manufacturing stage
$IF_{(en_pm)}$	=	Influencing Factor rated on a scale of 0-10 for the Environment component of Pre-manufacturing stage
n	=	Number of influencing factors considered

Analytical Foundation of Product Design for Sustainability (*Cont'd)*

$$PSI_{en} = [PSI_{(en_pm)} + PSI_{(en_m)} + PSI_{(en_u)} + PSI_{(en_pu)}]/4$$

where,

$PSI_{(en_pm)}$ = Product Sustainability Index for Environment component of Pre-manufacturing stage

$PSI_{(en_m)}$ = Product Sustainability Index for Environment component of Manufacturing stage

$PSI_{(en_u)}$ = Product Sustainability Index for Environment component of Use stage

$PSI_{(en_pu)}$ = Product Sustainability Index for Environment component of Post-use stage

The overall product sustainability index (PSI_{TLC}) for a product over its total life-cycle

$$PSI_{TLC} = PSI_{so} + PSI_{en} + PSI_{ec}$$

PSI_{so} = PSI for Society Component

PSI_{en} = PSI for Environment Component

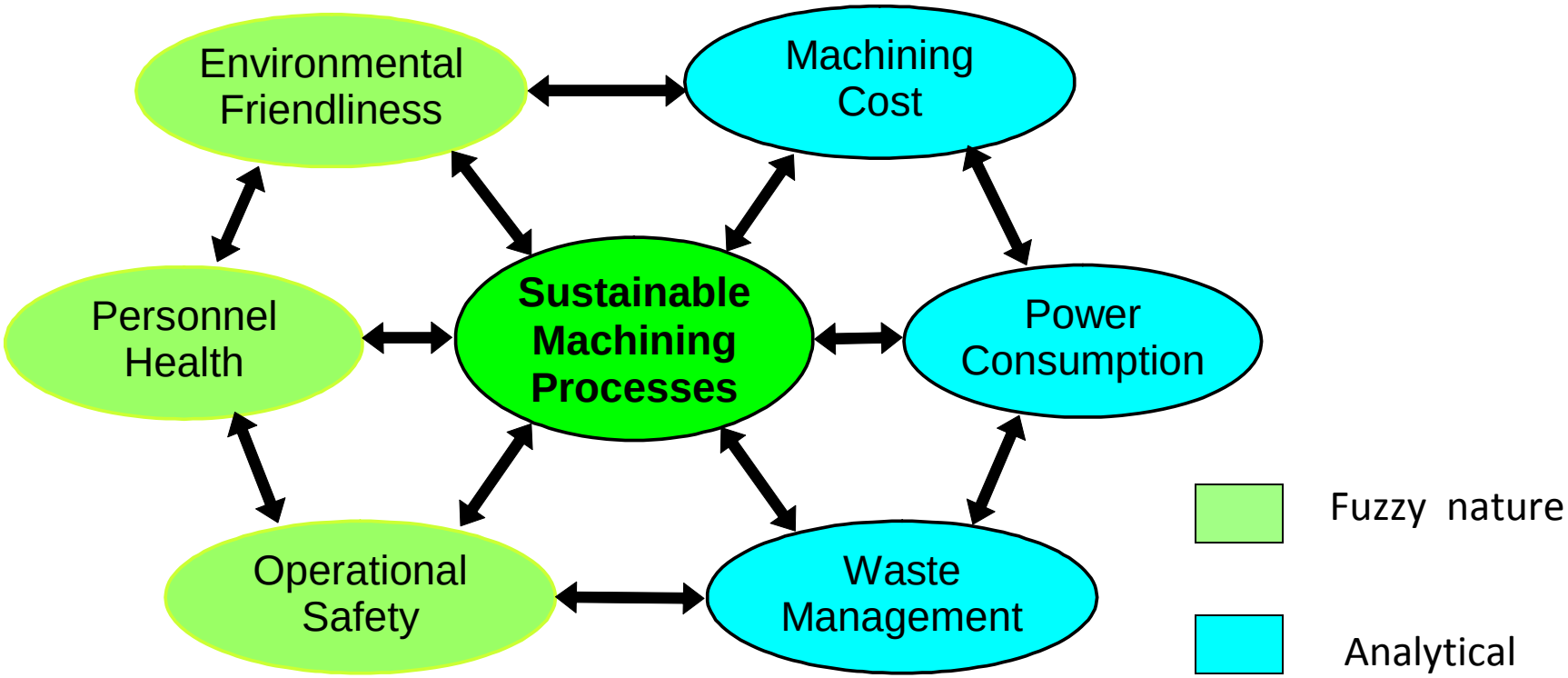
PSI_{ec} = PSI for Economy Component

A Framework for Comprehensive Total Life-cycle Evaluation of Product Sustainability

Sustainability Components		Influencing Factors in the Product Life-cycle Stages: Pre-manufacturing	Score out of 10	Manufacturing	Score out of 10	Use	Score out of 10	Post-use	Score out of 10		
	Environment	Material Extraction	7	Production Energy Used	7	Emissions	9	Recyclability	7		
		Design for Environment	8	Hazardous Waste Produced	9	Functionality	8	Remanufacturability	8		
		Material Processing	6	Renewable Energy Used	8	Hazardous Waste Generated	9	Redesign	7		
								Landfill Contribution	7	**(%) PSI_{en} =**	77.29
		(%) $PSI_{(en_pm)}$ =	70	(%) $PSI_{(en_m)}$ =	80	(%) $PSI_{(en_u)}$ =	86.67	(%) $PSI_{(en_pu)}$ =	72.5		
	Society	Worker Health	8	Work Ethics	7	Product Pricing	7	Take-back Options	7		
		Work Safety	8	Ergonomics	7	Human Safety	9	Re-use	6		
		Ergonomics	7	Work Safety	8	Upgradeablility	7	Recovery	7		
						Complaints	8			**(%) PSI_{so} =**	73.54
		(%) $PSI_{(so_pm)}$ =	76.67	(%) $PSI_{(so_m)}$ =	73.33	(%) $PSI_{(so_u)}$ =	77.5	(%) $PSI_{(so_pu)}$ =	66.67		
	Economy	Raw Material Cost	6	Production Cost	6	Maintenance Cost	7	Recycling Cost	7		
		Labor Cost	3	Packaging Cost	7	Repair Cost	6	Disassembly Cost	8		
				Energy Cost	8	Consumer Injury Cost	8	Disposal Cost	4		
				Transportation Cost	5	Consumer Warranty Cost	7	Remanufacturing Cost	7	**(%) PSI_{ec} =**	61.25
		(%) $PSI_{(ec_pm)}$ =	45	(%) $PSI_{(ec_m)}$ =	65	(%) $PSI_{(ec_pu)}$ =	70	(%) $PSI_{(ec_pu)}$ =	65		
		(%) PSI_{pm} =	63.89	**(%) PSI_{m} =**	72.78	**(%) PSI_{u} =**	78.06	**(%) PSI_{pu} =**	68.06	**(%) PSI_{TLC} =**	70.69

Symbol				
Score	Excellent 85-90%	Good 70-84%	Average 50-69%	Poor < 50%

Basic Sustainability Elements in Machining

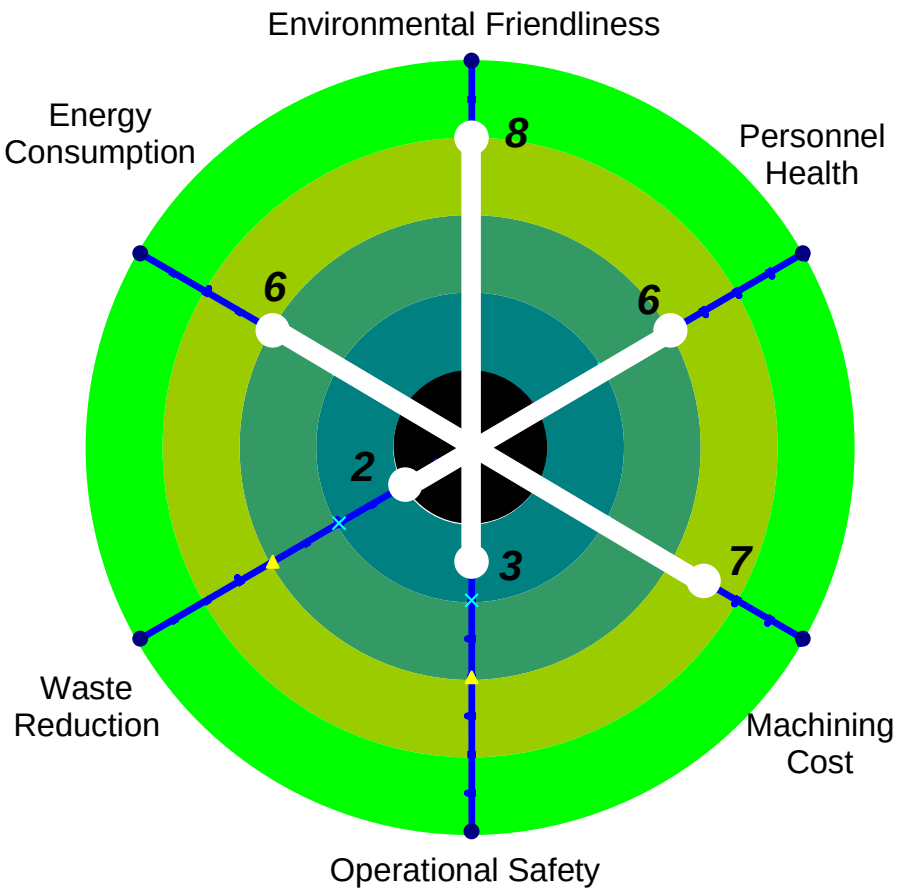


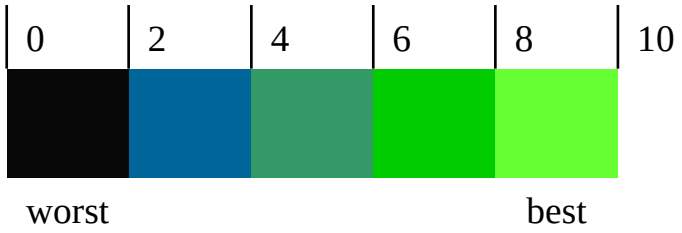
Regulating (Enforcing) Organizations

Methodologies to measure sustainability variables as well as regulations used to set the range of the variables can be obtained from many sources:

- National Institute for Occupational Safety and Health (NIOSH)
- Occupational Health and Safety Administration (OSHA)
- Environmental Protection Agency (EPA)
- Safety & Health Assessment & Research for Prevention (SHARP), etc.

Proposed Sustainability Rating System for Machining Processes





Sustainability Index: First Approach

Operational safety

+

Personnel health

+

Machining cost

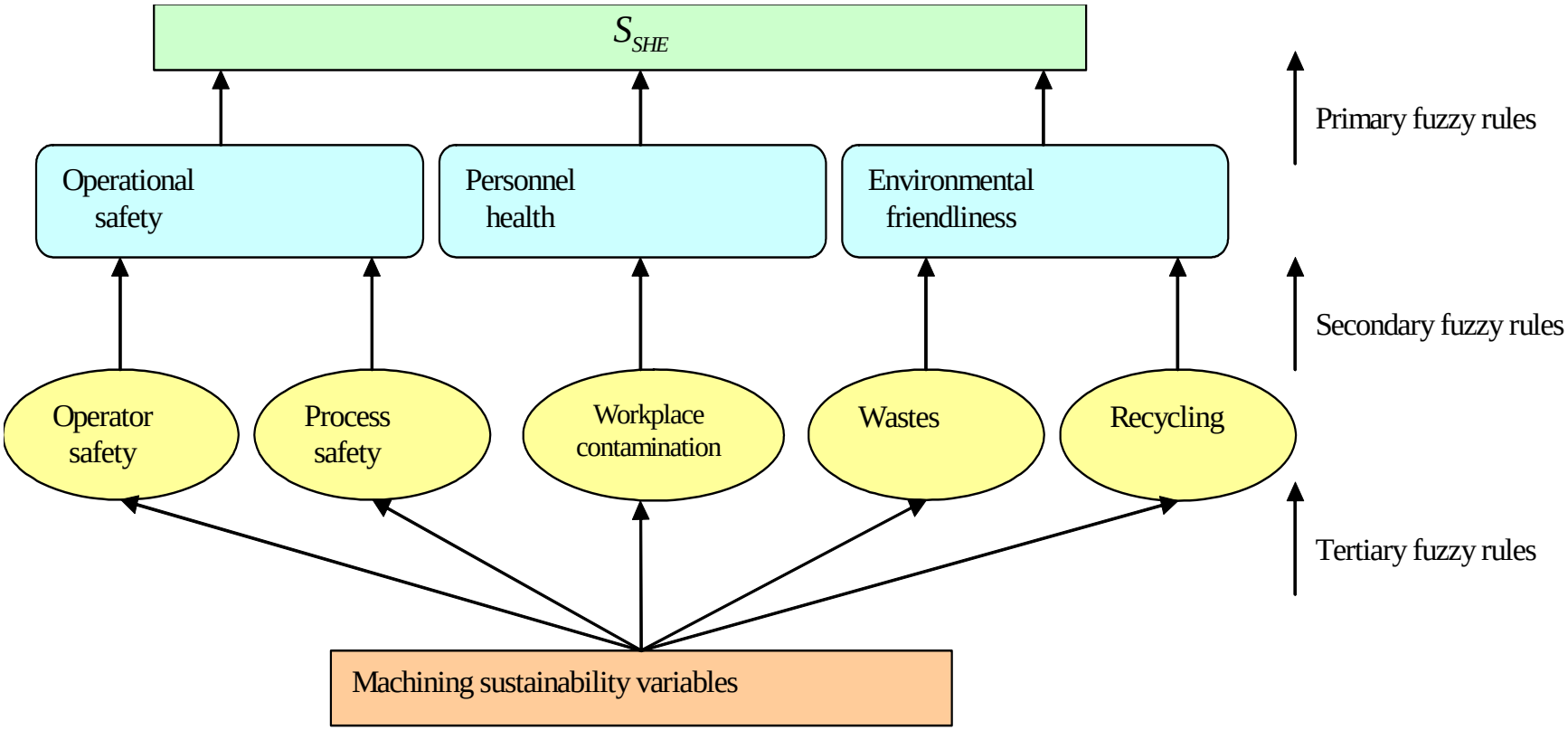
Power consumption

Waste management

Environmental friendliness

$$S = \underbrace{C_{MC} \cdot \left(\frac{MC_{\min} - MC}{MC_{\max} - MC_{\min}} + 1 \right) + C_{PC} \cdot \left(\frac{PC_{\min} - PC}{PC_{\max} - PC_{\min}} + 1 \right) + C_{CB} \cdot \left(\frac{CB - CB_{\min}}{CB_{\max} - CB_{\min}} \right)}_{f\,(V,\,f,\,d)} + \underbrace{S_{SHE}}_{F\,(s_i)}$$

Methodology for S_{SHE}



Optimization for Operational Sustainability Index

For the multi-pass turning operation problems,

$$\overline{S_{op}}(V_i, f_i, d_i, (i = 1,2,...N))$$

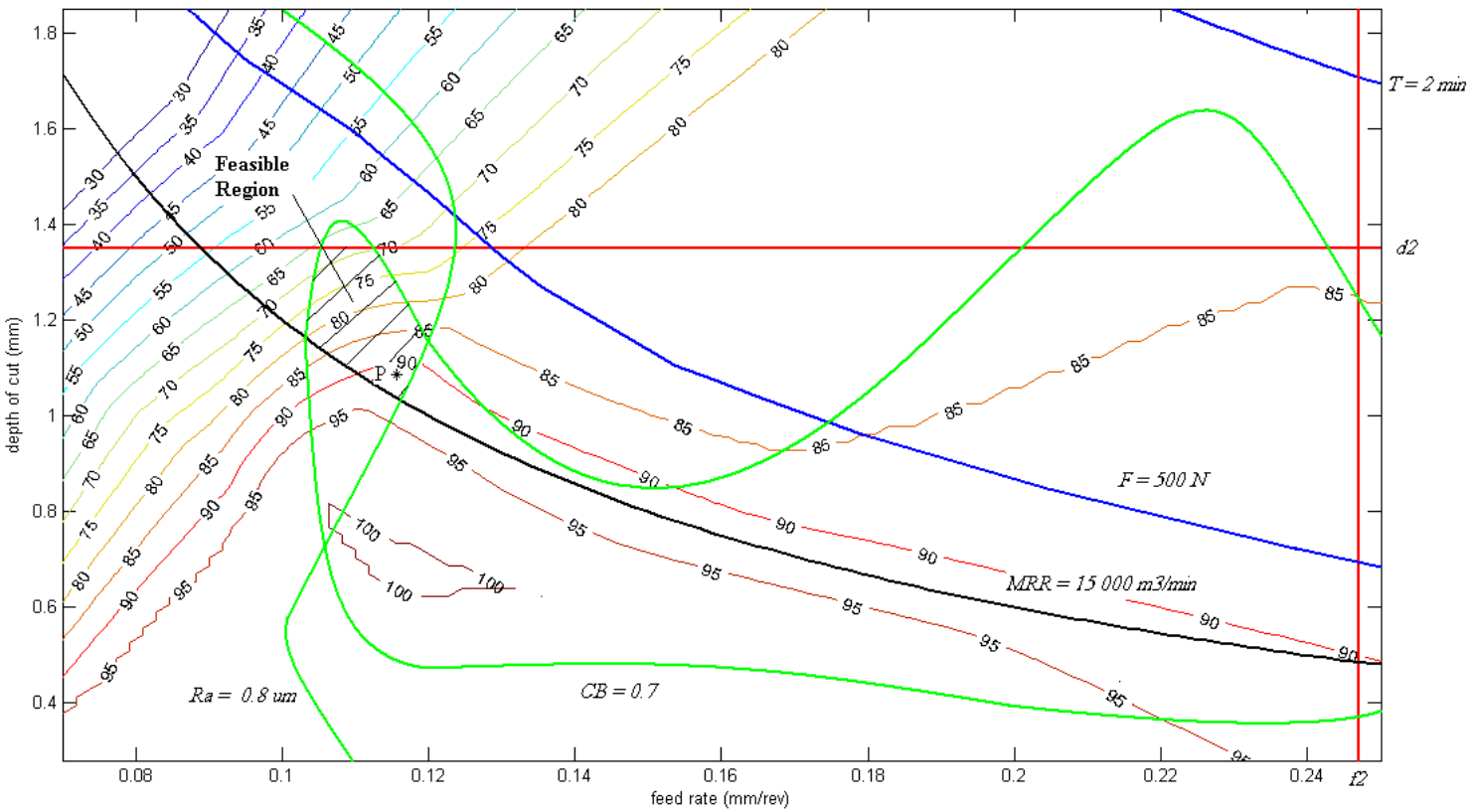
$$= \frac{1}{N}\sum_{i=0}^{N}\left[C_{MC}\cdot\left(\frac{MC_{\min} - MC_i}{MC_{\max} - MC_{\min}} + 1\right) + C_{PC}\cdot\left(\frac{PC_{\min} - PC_i}{PC_{\max} - PC_{\min}} + 1\right) + C_{CB}\cdot\left(\frac{CB_i - CB_{\min}}{CB_{\max} - CB_{\min}}\right)\right]$$

where the N parameter is the number of passes in a turning operation, V_i is the cutting speed, f_i is the feed rate and d_i is the depth of cut for each pass

Constraints are presented as :

$$MC_{\min} \le MC_i \le MC_{\max}, PC_{\min} \le PC_i \le PC_{\max}, CB_{\min} \le CB_i \le CB_{\max}, (i = 1,2,...N)$$

Contour Plot (Finishing)



Feasible region in finish turning, V = 150 m/min, d_t = 2.7 mm

$$[C_{MC}, C_{PC}, C_{CB}] = [0.8, 0.15, 0.05]$$

Sustainable Manufacturing Metrics for Environment

Sustainable Manufacturing Metrics for Environment	Product	Manufacturing Process	Enterprise Level	SC Level
% Sourcing from Environmentally sensitive areas	★	★		
Modularity				
Eco-effi				
Environmenta				
Energy Intensi				
Unusable heat				
Landfill : (% of				
Minim				
Packaging re				
Tap				

Sustainable Manufacturing Metrics for Environment	Manufacturing Process
% of Toxic/hazardous raw material usgae	★
Carbon footprints (tons/yr)	★

Sustainable Manufacturing Metrics for Environment	Enterprise Level
Number of payloads per miles (transportation energy)	★
Eco-effici	
Unusable hea	
Landfill : (% of residues in landfill or tons of residues disposed/ year)	★
Tapping embedded product energy (%)	★

Sustainable Manufacturing Metrics for Environment	SC Level
Number of payloads per miles (transportation energy)	★
% of Environmentally responsible suppliers	★
Carbon footprints (tons/yr)	★
Ozone equivalents (tons/yr)	★
Sulphur-oxides (tons/yr)	★
Nitrous-oxides (tons/yr)	★
% of Energy usage in Logistics	★
Packaging residues (amount in tons/million units in usage)	★
Tapping embedded product energy (%)	★
% Adherence to environmental laws	★

Sustainable Manufacturing Metrics for Economy

Sustainable Manufacturing Metrics for Economy	Product	Manufacturing Process	Enterprise Level	SC Level
Profit				
COGS				
Value				
% sale				
Total c				
Wareh				
Dispos				
Cost o				
Level c				
Accura				
Accura				
Produc				
Time r				
Time f				
Design				
Level c				
Educa				
Level c				
Level c				
Invento				

Sustainable Manufacturing Metrics for Economy	Product	Manufacturing Process	Enterprise Level	SC Level
Work in process				
Capacity utilizat				
Disposal cost				
Cost of determin				
Cost of recoverin				
Cost of disasser				
Scrap rate				
Product cycle ti				
Planned process				
Manufacturing le				
Time required to				
Time required to				
Cycle time impr				
Time for required				
Design/redesign				
Level of recyclin				
Level of design f				
Supplier ability t				
Production flexib				
Capacity flexibili				

Sustainable Manufacturing Metrics for Economy	Product	Manufacturing Process	Enterprise Level	SC Level
Information carrying c				
% sales of new produ				
Capital tie-up costs				
Training cost				
Total cost of resourc				
Manufacturing cost				
Work in process				
Inventory cost				
Inventory turnover rat				
Cost of illness				
Distribution costs				
Delivery efficiency				
Warranty/returns pro				
Cost of recovering pr				
Cost of categorizing				
Perfect order fulfillme				
Perfect purchase ord				
% invoices with billin				
Accuracy of market/r				
Cash-to-cash cycle t				
Time required to proc				
Time required to proc				
capacity flexibility				
delivery flexibility				
responsiveness to urgent deliveries				

Sustainable Manufacturing Metrics for Economy	SC Level
Information carrying cost	★
COGS	★
% of late or wrong supplier delivery	★
Landed cost	★
Total cost of resources	★
Capacity utilization as incoming stock level, WIP, scrap, FG	★
Inventory cost	★
Stock capacity	★
Stockout probability	★
% of excess/lack of resource within a period	★
Disposal cost	★
Distribution costs	★
Cost of recovering product	★
Cost of categorizing products for 6R	★
Cost of disassembly	★
Perfect order fulfillment	★
Level of supplier's defect-free deliveries	★
On-time arrival %	★
Customer complaints	★
Accuracy of market/regulatory information	★
Total SC response time	★
Time required to produce a new product mix	★

Sustainable Manufacturing Metrics for Society

Sustainable Manufacturing Metrics for Society	Product	Manufacturing Process	Enterprise Level	SC Level
Eliminate corruption and Bribery			★	★
Revenue from customers				★
% of suppliers that fulfill social criteria			★	
Cost invested in indentifying supplier's social practices				★
Number of supplier training sessions				
Number of suppliers effected through identity fraud				
Jobs classified by type and country				
Proportion of staff covered by industry wide collective tariff agreements				
Donations and sponsoring				
Diversity				
% of cost invested on improving societal impact awareness				
Number of marketing events conducted targeting vulnerable groups				
% of production allocated to supply developing countries				
% of lower segment customers satisfied				
Number of returning customers, time allocated for post–sales etc.				
Number of fraud complaints (customers)				
Lead time between recall initiation and product available in system				
% cost/ time invested in replacement offers				
Lead time between complaint acceptance and delivery of product or service				
Number of employees lost because of personal or interpersonal conflicts				

Closed-loop Sustainable Supply Chain Management (SSCM)

Focal Manufacturing Company

Other Manufacturing Companies

RLP = Reverse Logistics Providers

Conventional SC focus

Tier 3 to Initial Suppliers | Tier 2 Suppliers | Tier 1 Suppliers | Tier 1 Customers | Tier 2 Customers | Tier 3 to Consumers/ End-users | Tier 1 RLP's | Tier 2 RLP's | Tier 3 to Disposal

Initial Suppliers | Tier 3 to n Suppliers | Tier 3 to end Customers | Consumers/End-users | Tier 3 to Disposal | Disposal

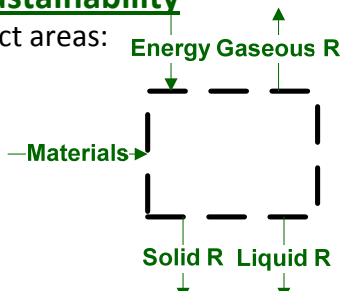
Product Life-cycle Stages: Pre-Manufacturing | Manufacturing | Use | Post-use

6R Applications: Recycle | Redesign | Remanufacture | Reuse | Recover | Reduce

Environmental sustainability

Environmental impact areas:

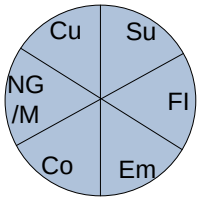
- **Material Use**
- **Energy Use**
- **Solid Residue**
- **Liquid Residue**
- **Gaseous Residue**



Societal sustainability

Stakeholder groups:

- Suppliers (Su)
- Financial Institutions (FI)
- Customers (Cu)
- Employees (Em)
- Community (Co)
- NGO's/Media (NG/M)



Economic sustainability

Business Dimensions:

- Cash Flow and Growth Management
- Balance Sheet (Asset Utilization)
- Productivity and Efficiency
- Demand Management
- Capitalization

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