ENPM 692
MANUFACTURING AND AUTOMATION

Unit Manufacturing Processes

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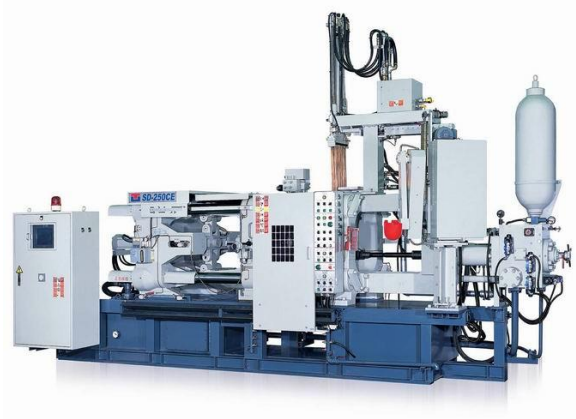
Email: mmani@umd.edu

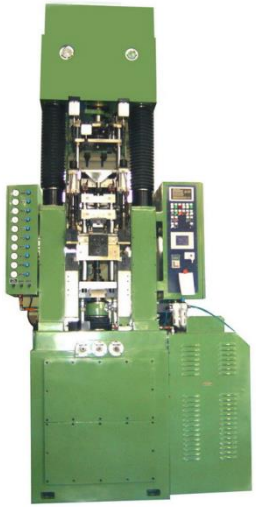
Time: Wednesdays 7:00pm - 9:40pm
Location: JMP 2222

A Flavor Of Manufacturing

Injection Molding



Die Casting



PM Press

A look into the Processes

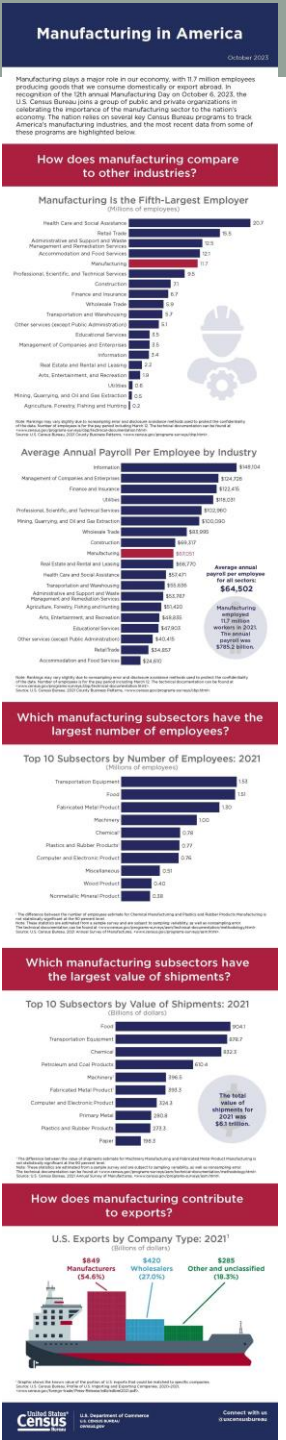
Image Source: Internet, Video: Youtube

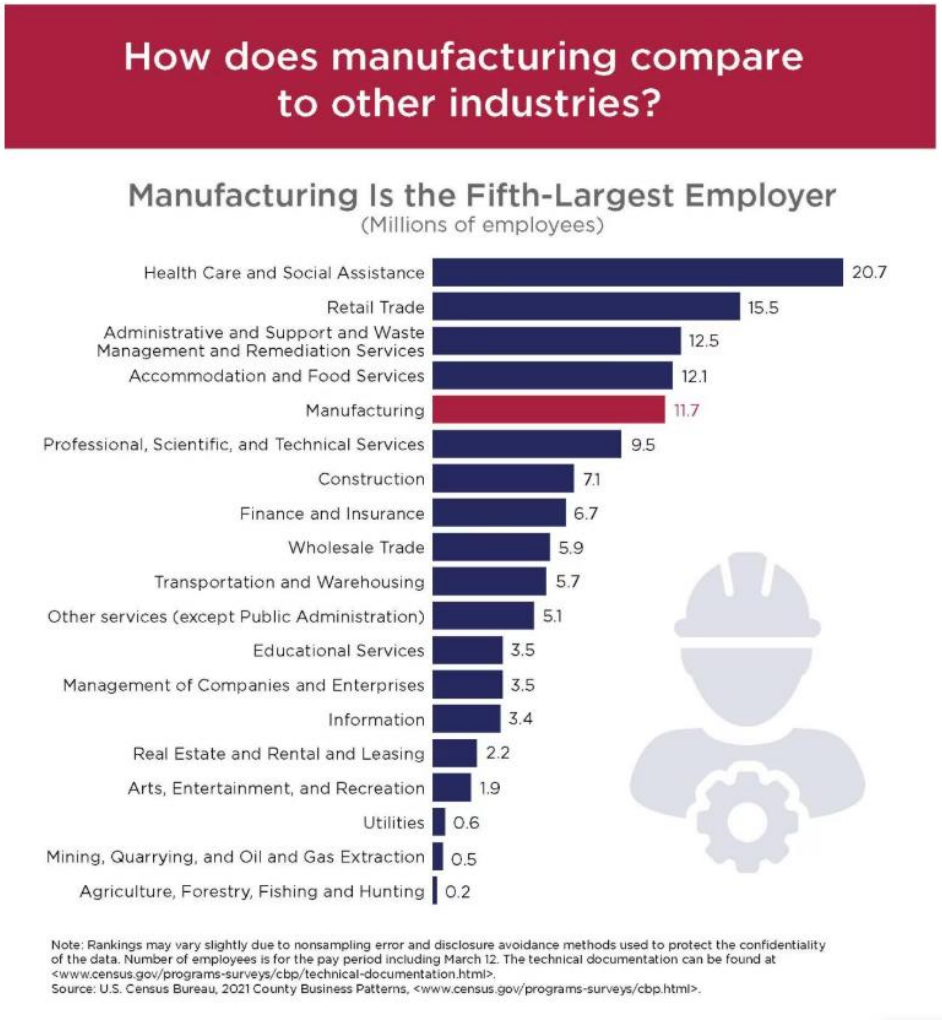
Why Manufacturing Matters

- When shop floor manufacturing jobs depart, other jobs go with them- and with those jobs goes the ability to create and innovate.
- When it comes to advanced manufacturing, we must compete if we want to hold onto our role as global innovators and entrepreneurs.
- Domestic manufacturing is also the key to more balanced trading relationships.

The Importance and Promise of American Manufacturing, Why It Matters if We Make It in America and Where We Stand Today--Michael Ettlinger and Kate Gordon, April 2011

Made in America

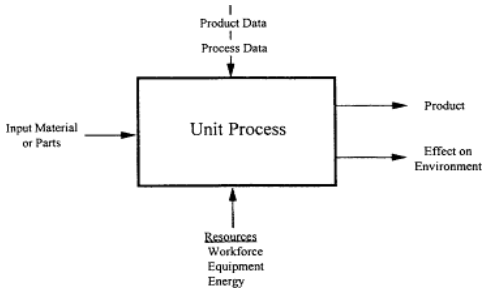




https://www.census.gov/library/visualizations/2023/econ/manufacturing-in-america.html

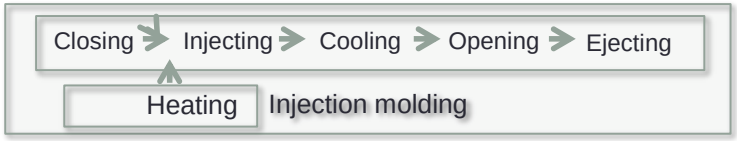
Basic Terminology

- *Unit Manufacturing Process (UMP):* individual steps required to produce finished goods by transforming raw material and adding value to the work-piece as it becomes a finished product.

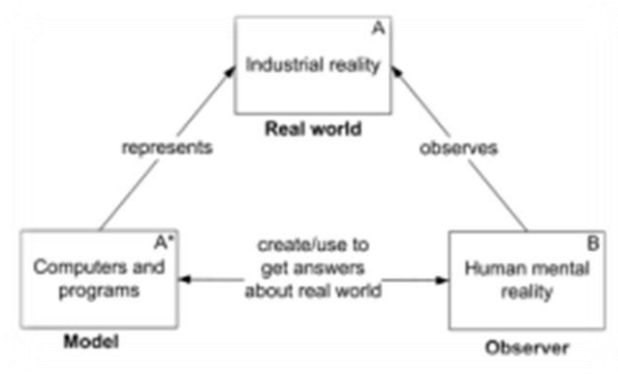


Source: NRC Report

- *Sub Processes or Unit Operations:* a sub-process (or unit-operation) is an inseparable and essential activity of the unit process.



- *UMP Information model:* a representation of entities, properties, and relationships enabling understanding of complex manufacturing processes/ systems.

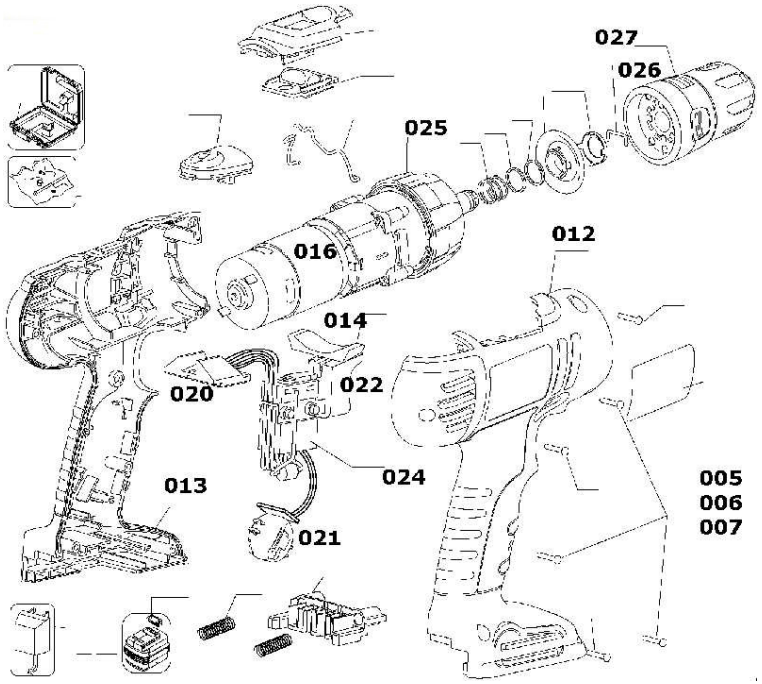


Source: Euler-Chelpin

From Product to “part and process”

DeWALT Screwdriver/Impact Driver

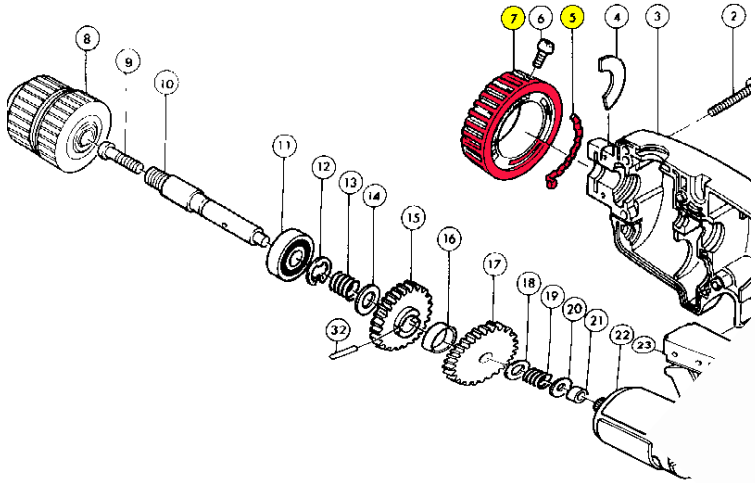
From Product to “part and process”



Part Description Function Process

Part	Description	Function	Manufacturing Process
001	Battery	Provide electricity	Injection Molding Purchase Assembly Line
002	Support Handle	Provide support for non-dominant hand	Injection Molding
003	Supp. Handle Screw	Secure Support Handle	Purchase
004	Nut	Secure Support Handle Screw	Purchase
005	Screw	Secure Case	Purchase
006	Screw	Secure Case	Purchase
007	Screw	Secure Case	Purchase
008	Casing Part	Hold in parts	Injection Molding
009	Casing Part	Hold in parts	Injection Molding
010	Strap	Helps to provide a secure grip	Purchase Folding
011	Plastic Plate	Provide drill information	Injection molding
012	Large Case R	Hold in parts	Injection Molding
013	Large Case L	Hold in parts	Injection Molding
014	Clutch Trigger	Move clutch	Injection Molding
015	Screw	Hold motor to chuck	Purchase

From Product to “part and process”



Component: Gears

Manufacturing Processes: PM Presses, Annealing, Machining, Brushing

Challenge

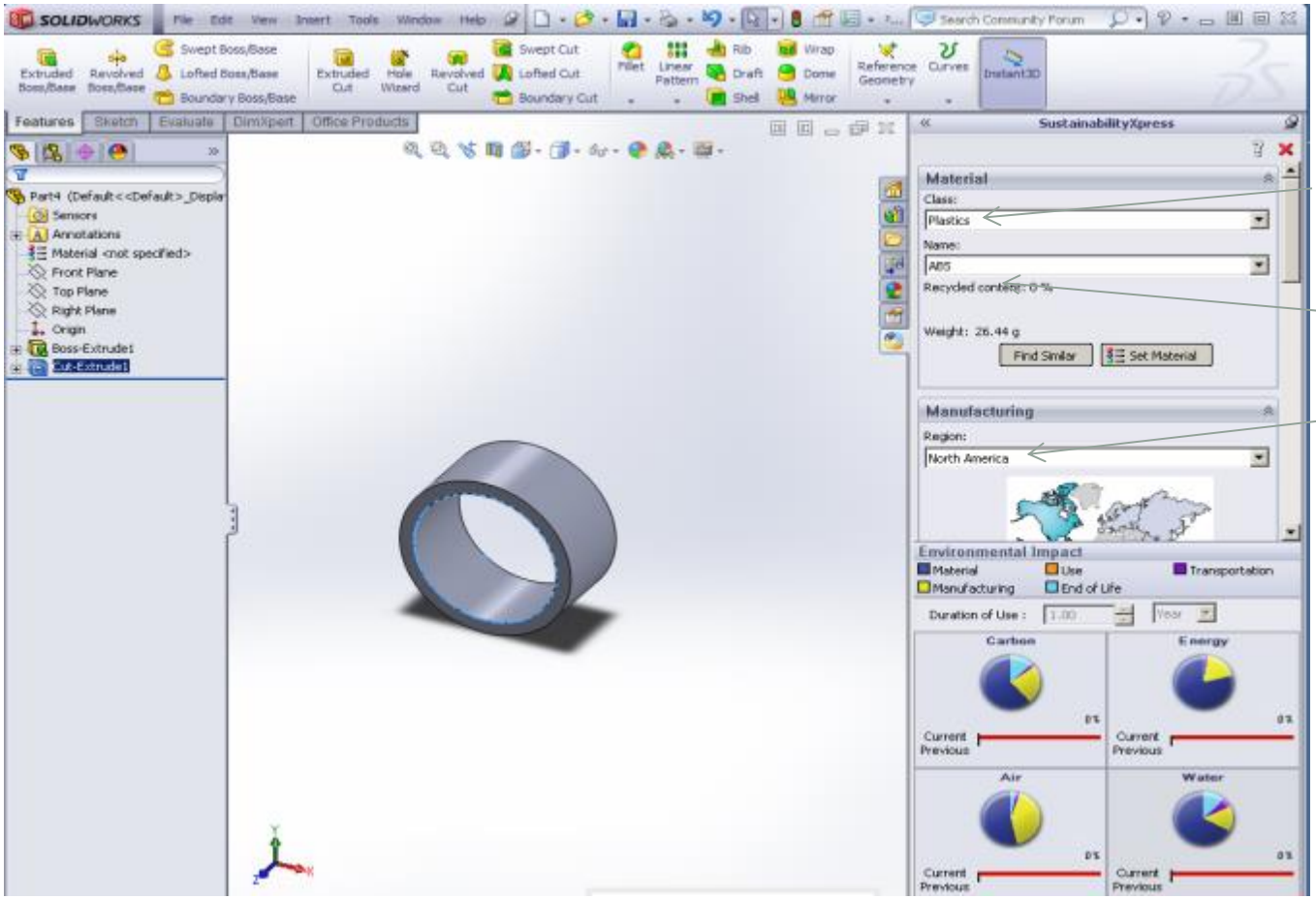
Measurement science and methodology to evaluate sustainability performance metrics (such as energy and material consumption, emissions, waste, and water usage) of unit manufacturing processes.

- Characterization methodology for sustainability
- Case studies -- to verify methodology and preliminary standards created based on a production model
- Standards -- Guide for Sustainability Improvement of Manufacturing Processes

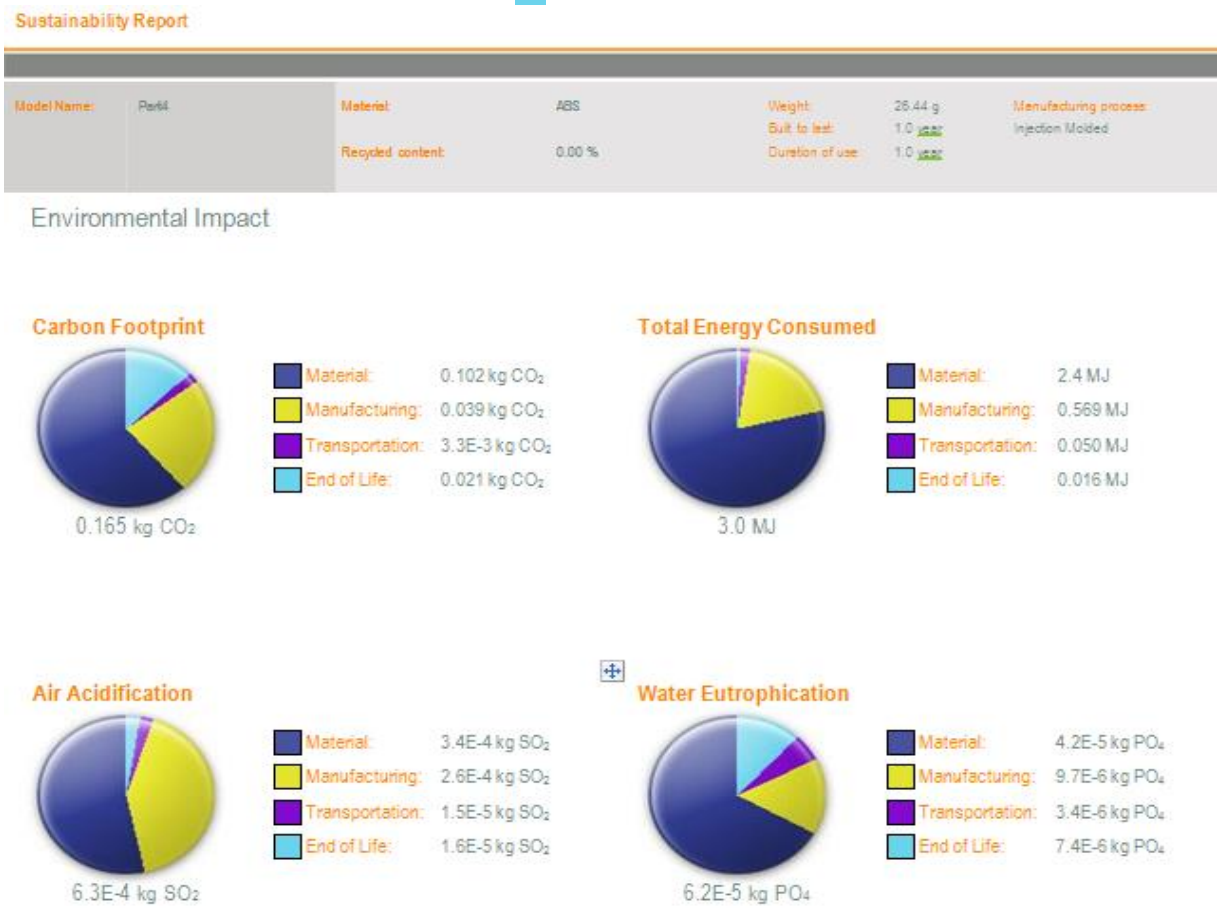
Technical Barriers

- Lack of measurement science to accurately compute the sustainability performance of manufacturing processes
- Use of ad-hoc methods to compute and unstructured data to report these metrics
- Lack of science-based methodology and associated guides for analytical and structured information models for computing sustainability metrics

Technical Barriers Sustainability Assessment: Current Methods

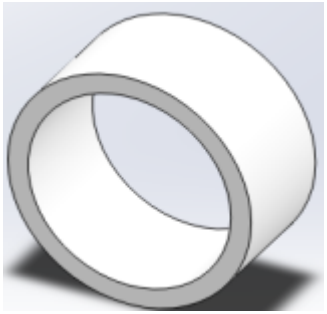


Technical Barriers Sustainability Assessment: Current Methods

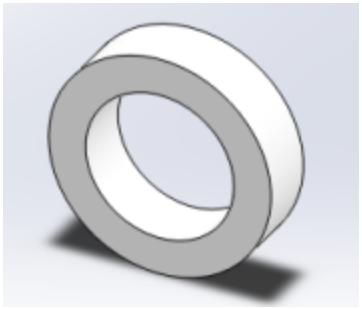


Technical Barriers Sustainability Assessment: Current Methods

- Baseline – design



- Modified – design



Same weight but part characteristics modified

No change in the generated sustainability report

Technical Barriers: Limitations of present methods

- LCA based on regional averages
- Considers per unit mass of material
- Manufacturing specific information not fully accounted
- Lacks standard methods to establish a baseline for measurement and comparison purposes

Path Forward…

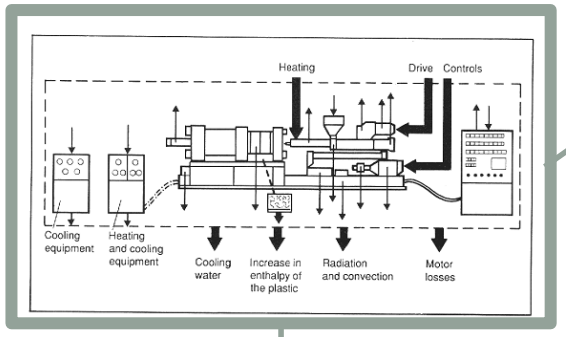
Towards a sustainability characterization methodology

Develop a science-based assessment methodology and structured information that defines:

1. methodology and measurement framework for sustainability characterization;
2. necessary analytical models and toolsets using a set of computable performance metrics;
3. generic sustainability characterization methodology to support repositories; and
4. standards for the components of sustainability characterization: performance metrics, information model, and process-specific data sets.

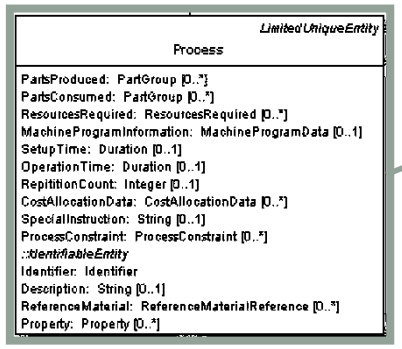
Methodology Illustration

Process Information



Process Parameters

Process Information Model



Computations

$$E_{Fill} = \frac{2^{\left(\frac{1}{s}+1\right)} 3^{\left(\frac{1}{s}\right)} \eta_0 e^{-\zeta(T-T_0)} Q^{\left(\frac{1}{s}\right)} L^2 W^{\left(1-\frac{1}{s}\right)}}{t^{\left(\frac{2}{s}\right)}}$$

where η_0 *belongs to :*

$$\eta = \eta_0 \dot{\gamma}^{\frac{1}{s}-1} e^{-\zeta(T-T_0)}$$

Standard Practices like ASTM D3641

Material Information

Sustainability Characterization

Key Performance Indicators

- [x] Energy and carbon dioxide (CO2)
- [x] Waste reduction
- [x] Water Usage
- [x] Emissions
- [x] Hazardous waste

Common Computable Sustainability Metrics

- [x] Total energy usage (MWh)
- [ ] Total gas & oil (MWh)
- [x] Total electricity (MWh)
- [ ] Total CO2 (tonnes)
- [x] Total water usage (m3)
- [x] Total discharged water (m3)
- [x] Total VOC emissions (tonnes)
- [ ] Total waste-at-cost (tonnes)
- [ ] Total waste-to-landfill (tonnes)

Manufacturing Processes Information Model

- General process information
- Sustainability specific information
- Best practices

! Including Information Acquisition and Usage Templates

Manufacturing Processes-Specific Data Sets

- [x] General process information
- [x] Sustainability specific information
- [x] Best practices

Injection Molding

Picture Source: WWW

Video Link: https://www.youtube.com/watch?v=b1U9W4iNDiQ

https://www.youtube.com/watch?v=5ZHyz9LBT08

Stages in Injection Molding

Regrinding, mixing, blending

Reground plastic + fresh plastic granules

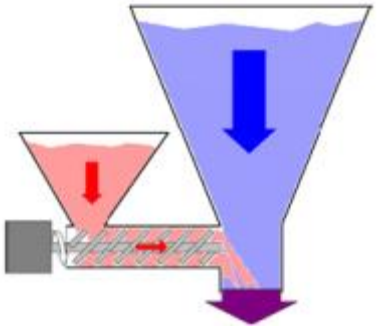
Close → Inject → Cool → Eject → Open

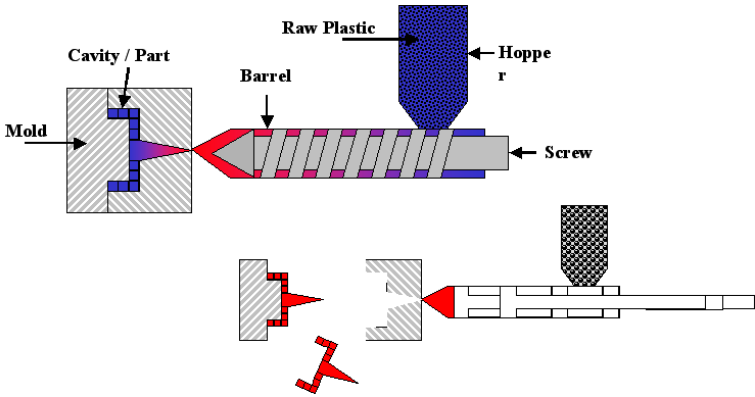
Heating

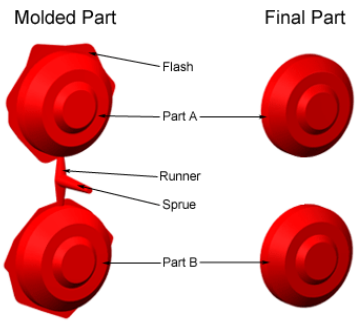
Injection molding

Semi finished solid part

Trimming extra plastic







Schematic of A Guideline

Part design

Material Databases (like MatWeb)

Volume, projected area, wall thickness, material, etc.

Initial process parameters

Density, injection temperature, injection pressure, etc.

Machine databases

Cavity details

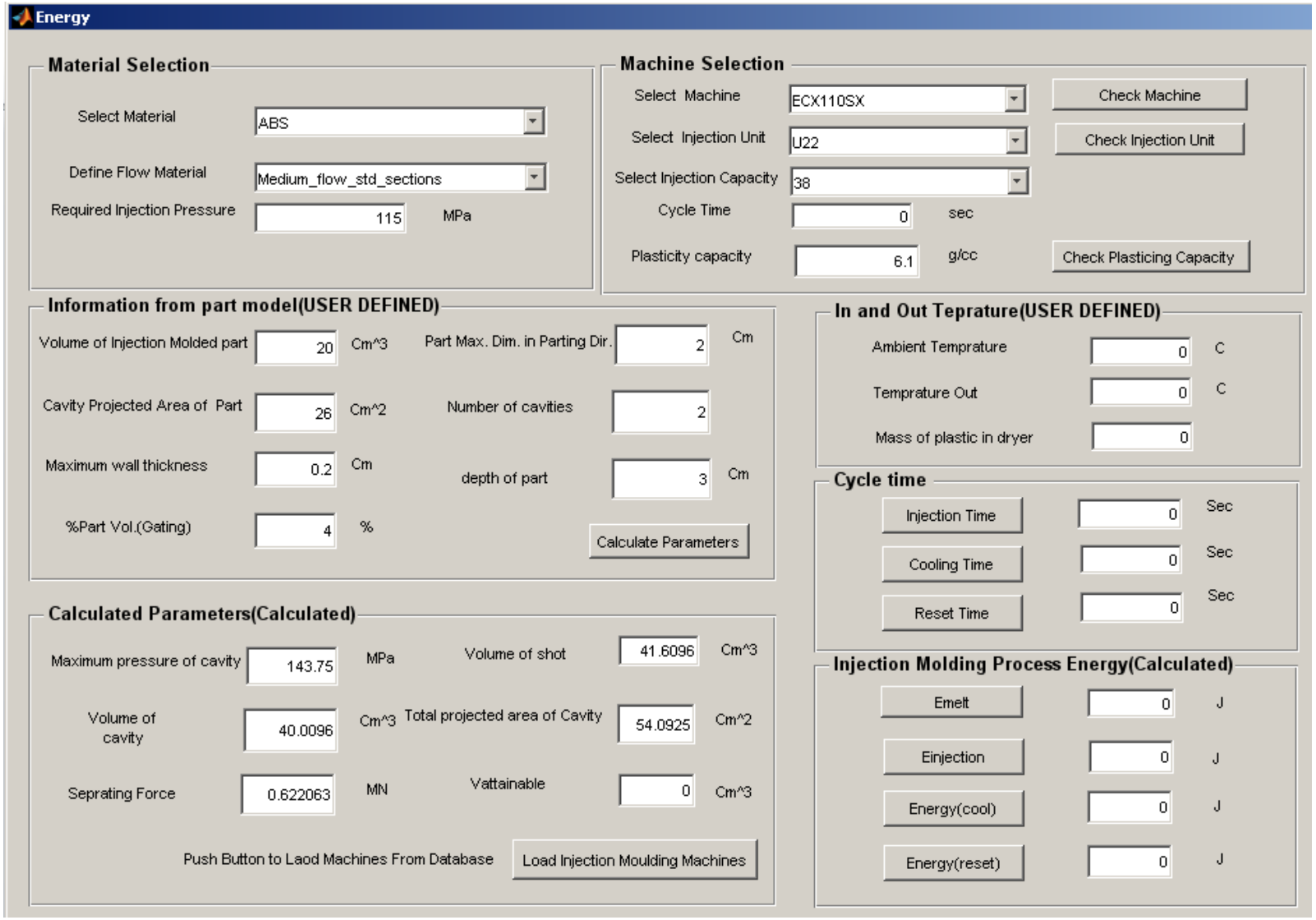
Machine selection and cycle time calculation

Theoretical energy requirements

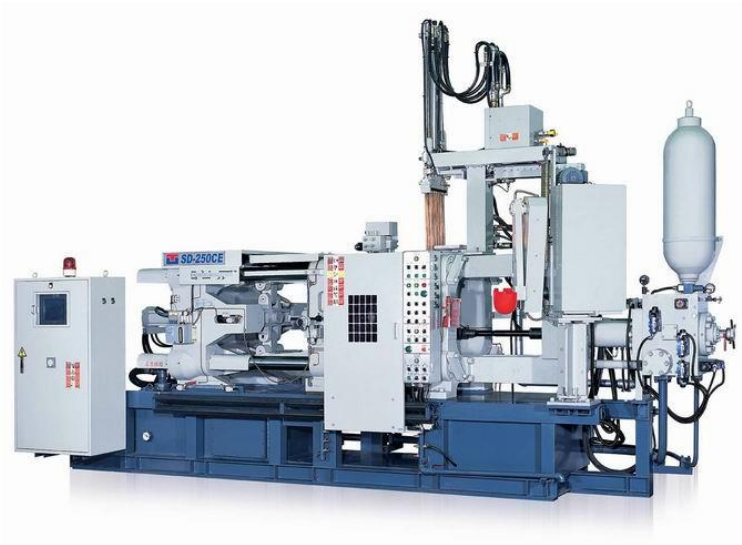
Estimated energy

Estimated energy per part

GUI: Energy estimation



Die-Casting



Picture Source: WWW

Video Link: https://www.youtube.com/watch?v=9mN1HFyg3iM

https://www.youtube.com/watch?v=0oibUY8KUQM

Die-Casting

- No way to thoroughly model/compute sustainability of UMPs
- Can meter certain indicators
- Some theoretical models for energy use exist, but leave out parts of the process
  - Thiriez & Gutowski, 2006
- Create more thorough theoretical energy model

Challenges

- No complete model exists
- Piece together parts from various different sources
- Make assumptions based on existing equations

Die-casting

Fundamentals of Die Casting Process

↓

Sustainable performance indicators & corresponding metrics

↓

Map inputs & outputs of process

↓

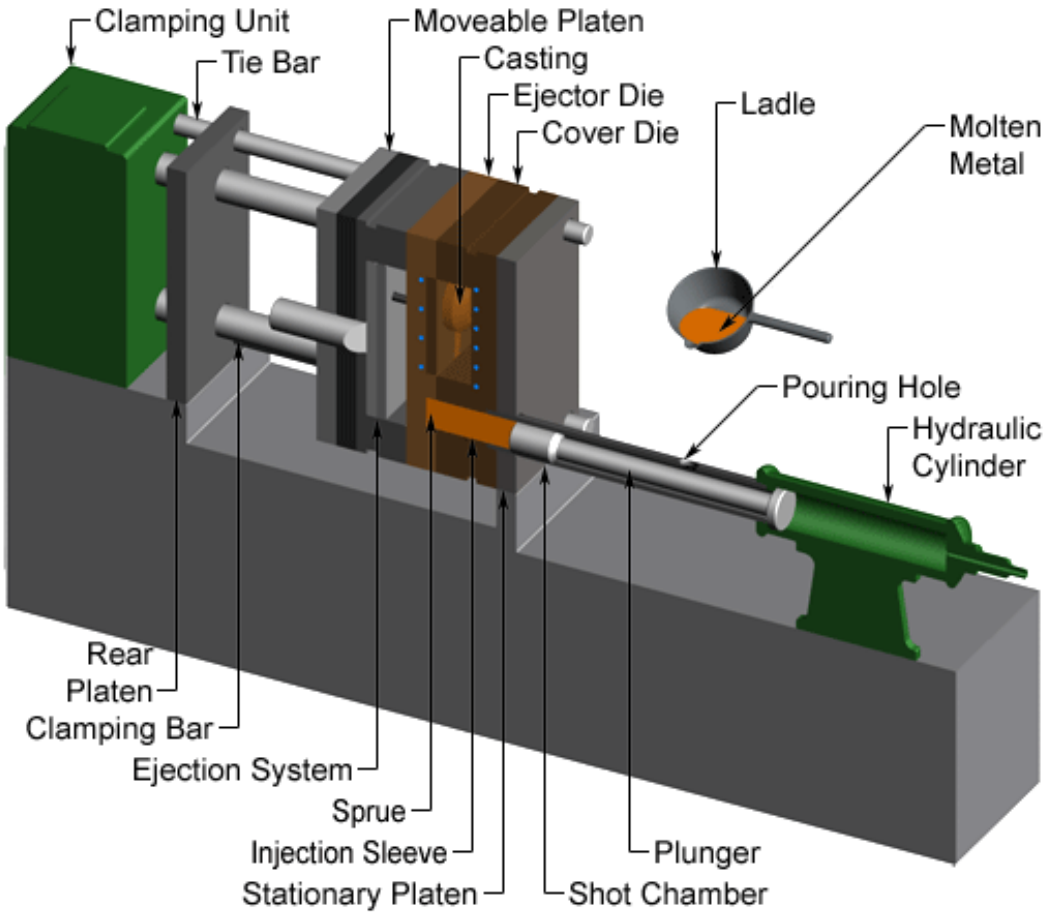
Identify/Formulate equations to theoretically calculate energy

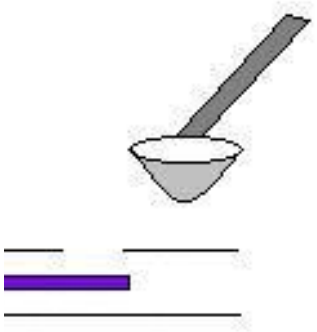
Source: biztrademarket.com

Die-casting

- Molten metal injected into reusable mold
- High pressure die casting most common
- Create complex shapes with fine details and fastening holes
- Examples: faucets, automobiles, toys

Die Casting Process

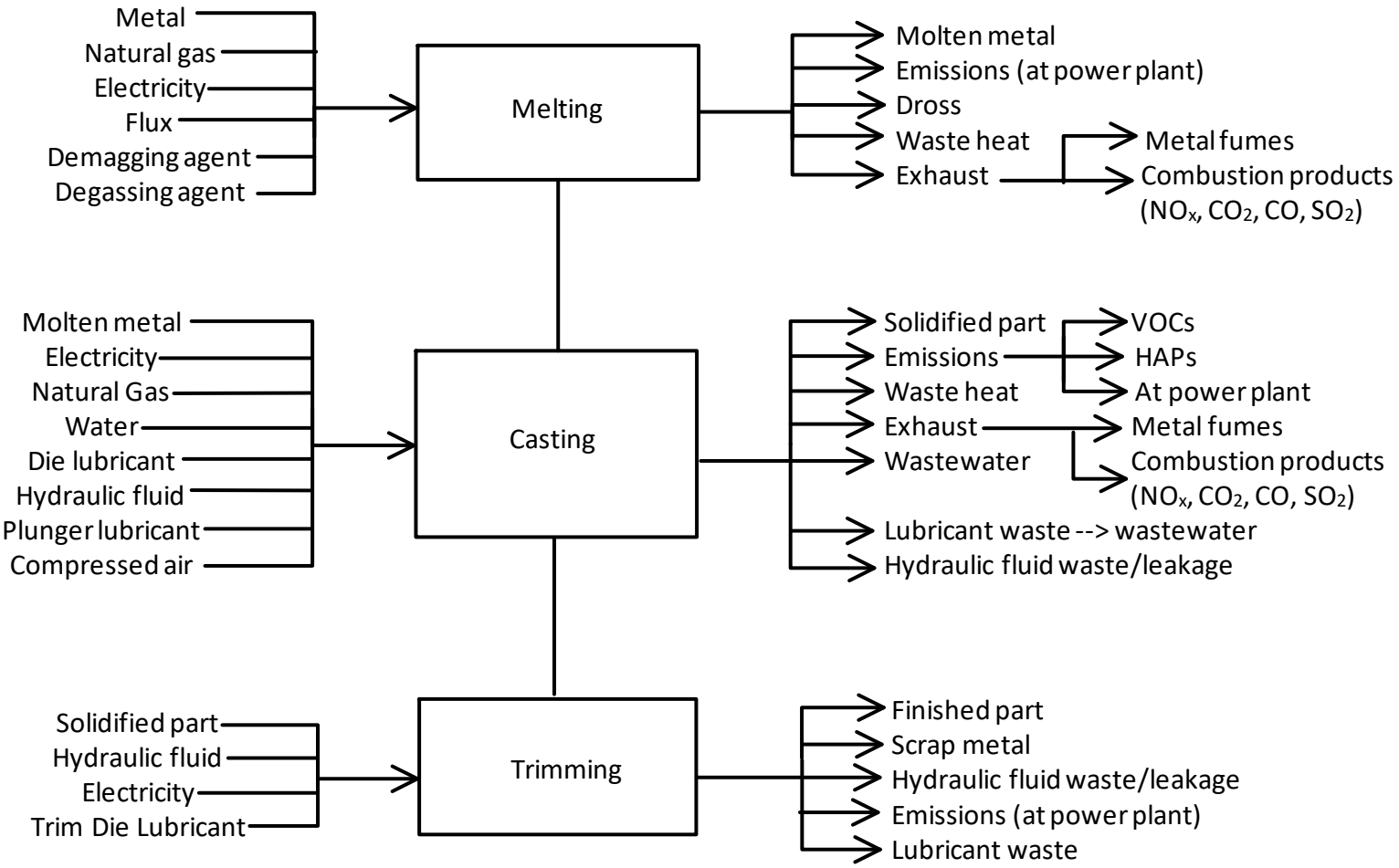




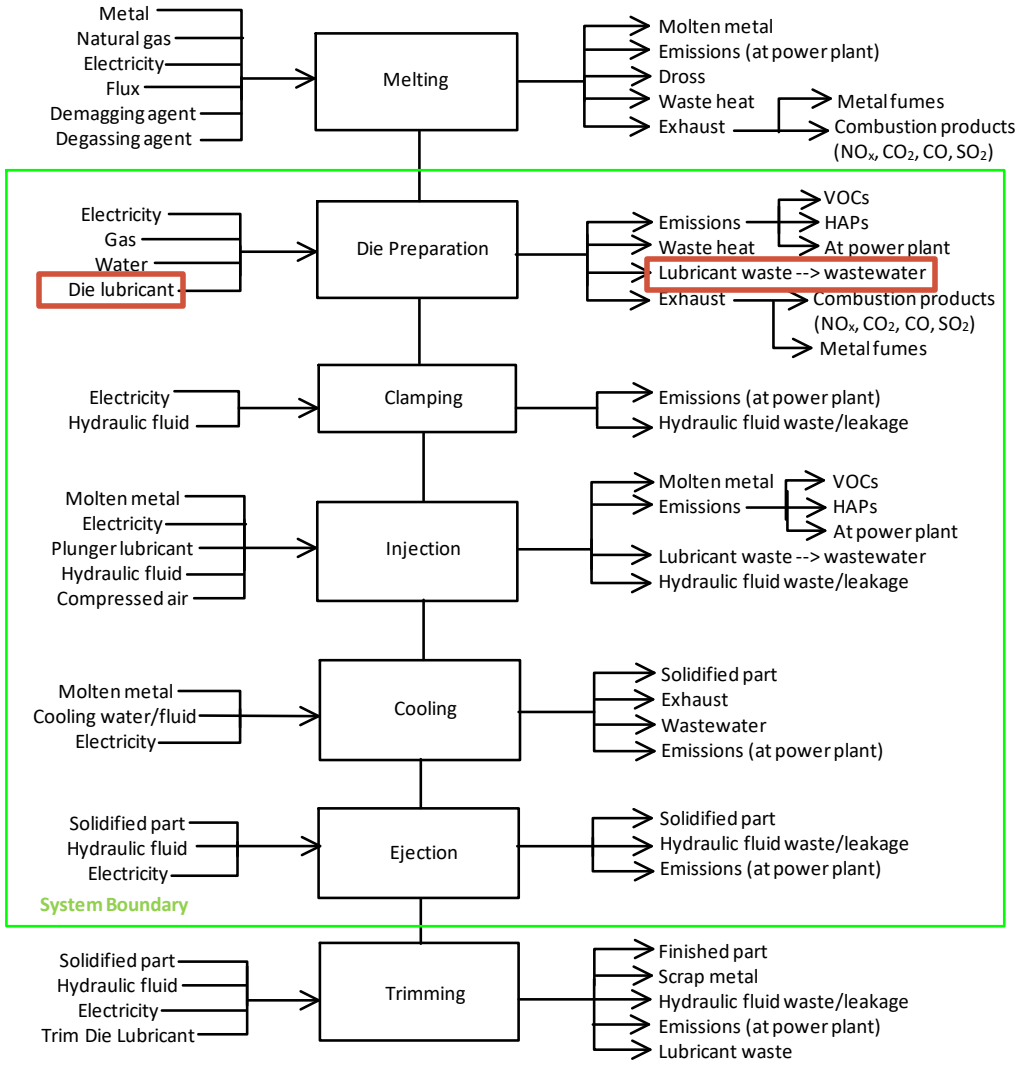
Performance Indicators

- Input indicators: (Singh, et al., 2012)
  - Energy use (kWh or MJ/kg)
  - Water use (m^3 or L)
  - Materials use (tons)
- Output indicators:
  - Product
  - Solid waste
  - Liquid waste
  - Air emissions

Input-Output Diagram



Input-Output Diagram



Theoretical Energy

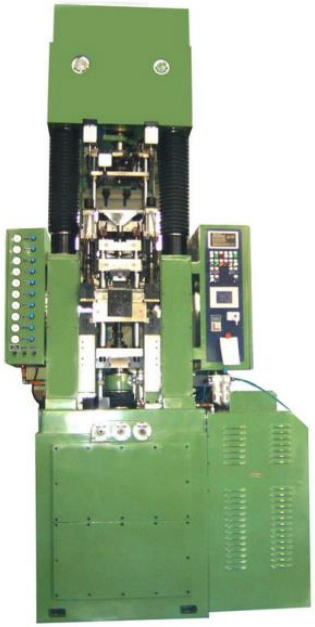
- Theoretical energy provides baseline for comparison
  - Ideal, therefore not achievable
  - Science-based

$$E\downarrow total = E\downarrow melt + E\downarrow fill + E\downarrow clamp + E\downarrow eject$$

(Thiriez & Gutowski, 2006)

- Packing, clamping, and ejecting energy account for less than 25% of total energy

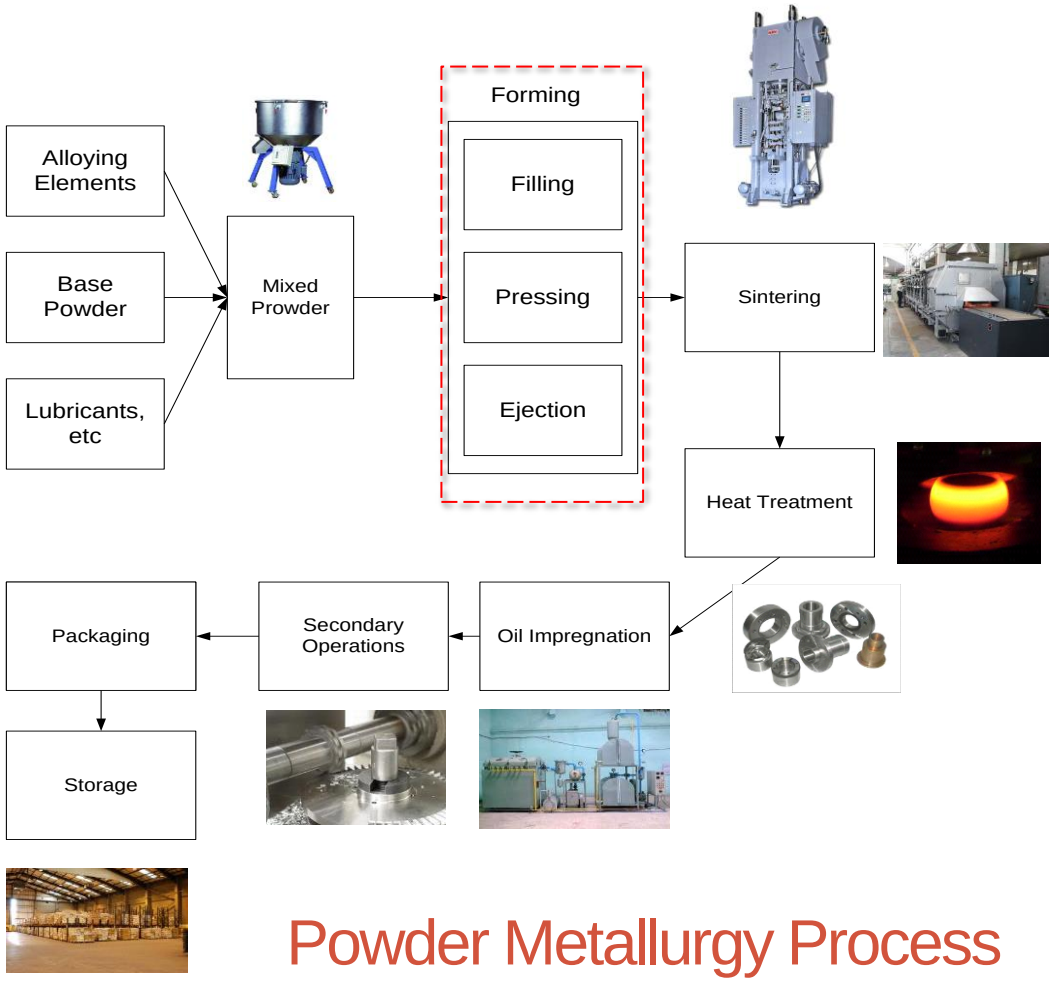
Powder Metallurgy



Picture Source: WWW

Video link: https://www.youtube.com/watch?v=azGg68B-Glk

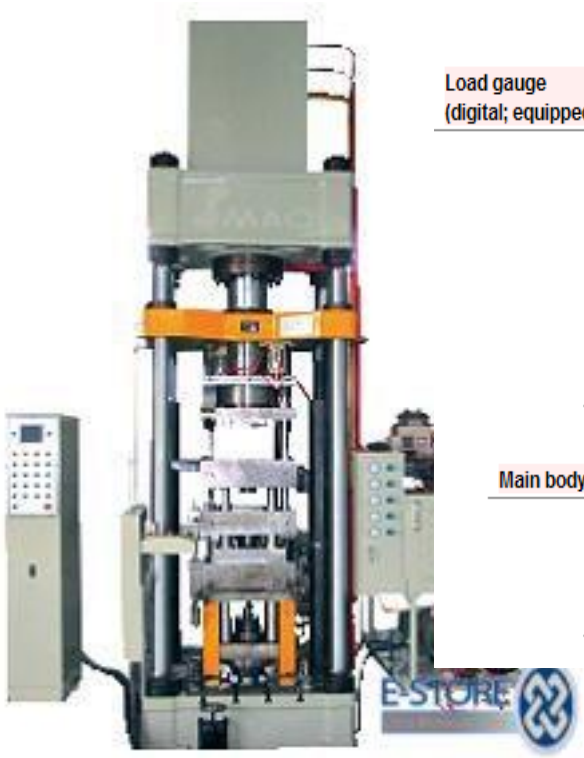
Outline of the PM Process

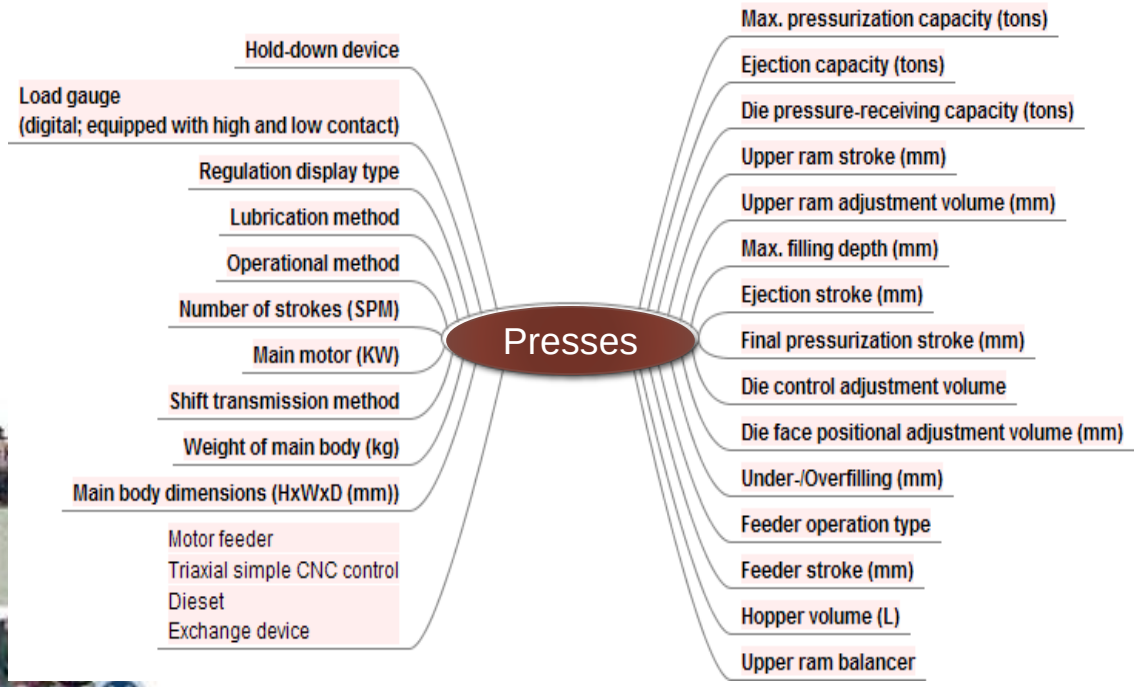


Powder Metallurgy Process

From Product to “part and process” information

PM Press Parameters





Significant/ Non-significant/ Controllable/ Computable? ENERGY

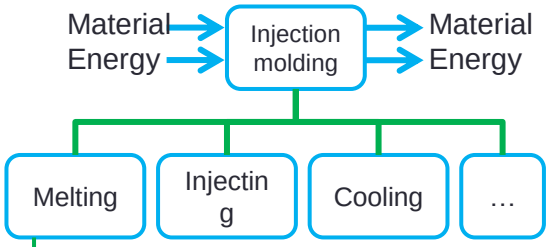
Computing Sustainability Metrics Requires Process/Material/Design Information

Real world:
Injection molding machine

How to increase energy and material efficiency in manufacturing?

Simulation with different parameters

Physical model of injection modeling process



Process property (P_i)

Rotation speed of screw
Temperature in cylinder
Pressure in cylinder

Material property (M_i)

Size of beads
Density
Melting point
Viscosity

Mold design property (D_i)

Volume

Computational model

Relationship among properties

Pressure in cylinder =
F(rotation speed of screw,
design of screw, viscosity of material)

Energy computational model for sub-processes

$E_i=f(P_i, M_i, D_i)$

Information parameter (handle) or given data

What Information Model Do You Need?

- Physical model (I/O model)
  - Information elements and relationships:
    - Process, materials, product design, machine, and their relationships and properties
    - Sustainability indicators
- Computational model
  - Property interactions
    - Mathematical functions
    - Rules in logics
    - Look-up table

Information Related Challenges

- No existing standard methods/tools for consistent evaluation and prediction of process sustainability
- Current ad-hoc methods result in inaccurate and ambiguous comparisons of processes
- No reliable formal information base for manufacturing sustainability decision support

Injection Molding Specific Information

Materials Knowledge / Material Stock Description

- Energy Use, Solid Waste, Atmospheric Emissions, Greenhouse Gases, and Waterborne Emissions Data for the production of the most common injection molding plastics.
  - *Cradle-To-Gate Life Cycle Inventory of Nine Plastic Resins and Four Polyurethane Precursors*
- Density, specific heat, crystallinity, thermal conductivity, recommended injection pressure, and recommended injection and ejection temperature for plastics can be calculated and/or obtained from the manufacturer.
  - *Injection Molding Processing Guide*

ROLE OF STANDARDS

Measurement Science: https://youtu.be/2j9BGVKbzS4

Objectives

How do we measure the performance of a manufacturing system?

- Identify deficits and barriers for manufacturing process characterization for performance measures.
  - Includes labor, equipment, materials, energy, costs, and information resources, among others.
- Gain industry perspective and ensure that methods and tools developed are useable and useful in industry.
- Identify requirements for sustainability metrics, process modeling, and measurement science
  - To support the development of a dynamic digital factory

Motivation: Why Measure

- Increase the visibility of the manufacturing resources within a company to improve ability to:
  - Reduce operational costs
  - Predict product costs
  - Schedule manufacturing resources
  - Improve product quality
  - Incorporate best practices
  - Control IP Protection
- Promote standards, methods, and tools to enable rapid implementation and dissemination of resource information and data for effective decision making.

Motivation: What to Measure

- Machines and Equipment
  - Energy
  - Direct CO_2
  - Water
  - Oils
  - Wastes
- Process Studies
  - Process settings
  - Task times
  - Throughput
- Inspection
  - Gaging
  - Metrology
  - Defects
  - Tolerances
  - Process capability
  - Scrap and rework
- Workers and Labor
  - Hourly rates
  - Injury rates
  - Health hazards
  - Required training

Foundational Definitions

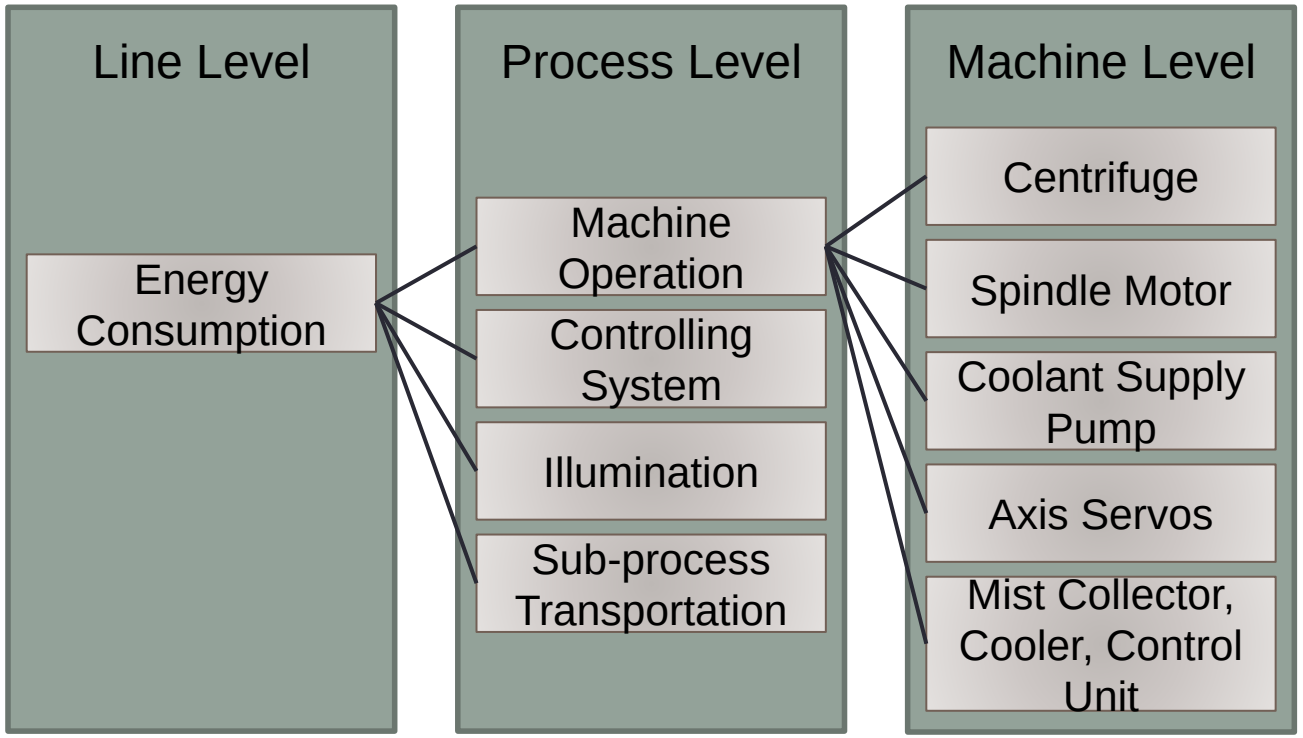
- Manufacturing resource
  - Any equipment, personnel, fixtures, gages, tooling, external accessories, software and control programs, and required operational settings used in manufacturing a product.
- Metric
  - Measurable quantity on which processes are evaluated and/or compared.
- Process model
  - Structured representation of the information associated with a manufacturing process.
- Measurement technique
  - Application of gages, tools, and other equipment to obtain a quantitative value for a metric.

Setting the Context: Metrics Development

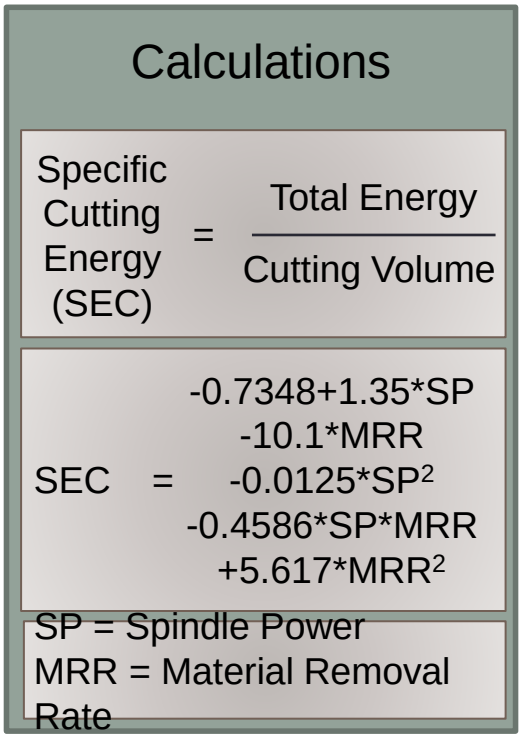
Performance Area	Performance Indicator	Performance Metric
Economic	Economic	Operating Cost
		Energy Consumption
Environmental	Energy	
	Emissions	GHG Emissions
		Waste to Landfill
Social	Waste	Waste to Recycle
	OH&S	Acute Injuries
		Chronic Illnesses

Adapted from: Eastlick, Haapala 2012. *Increasing the Utility of Sustainability Assessment in Product Design*

Setting the Context: Manufacturing Metrics

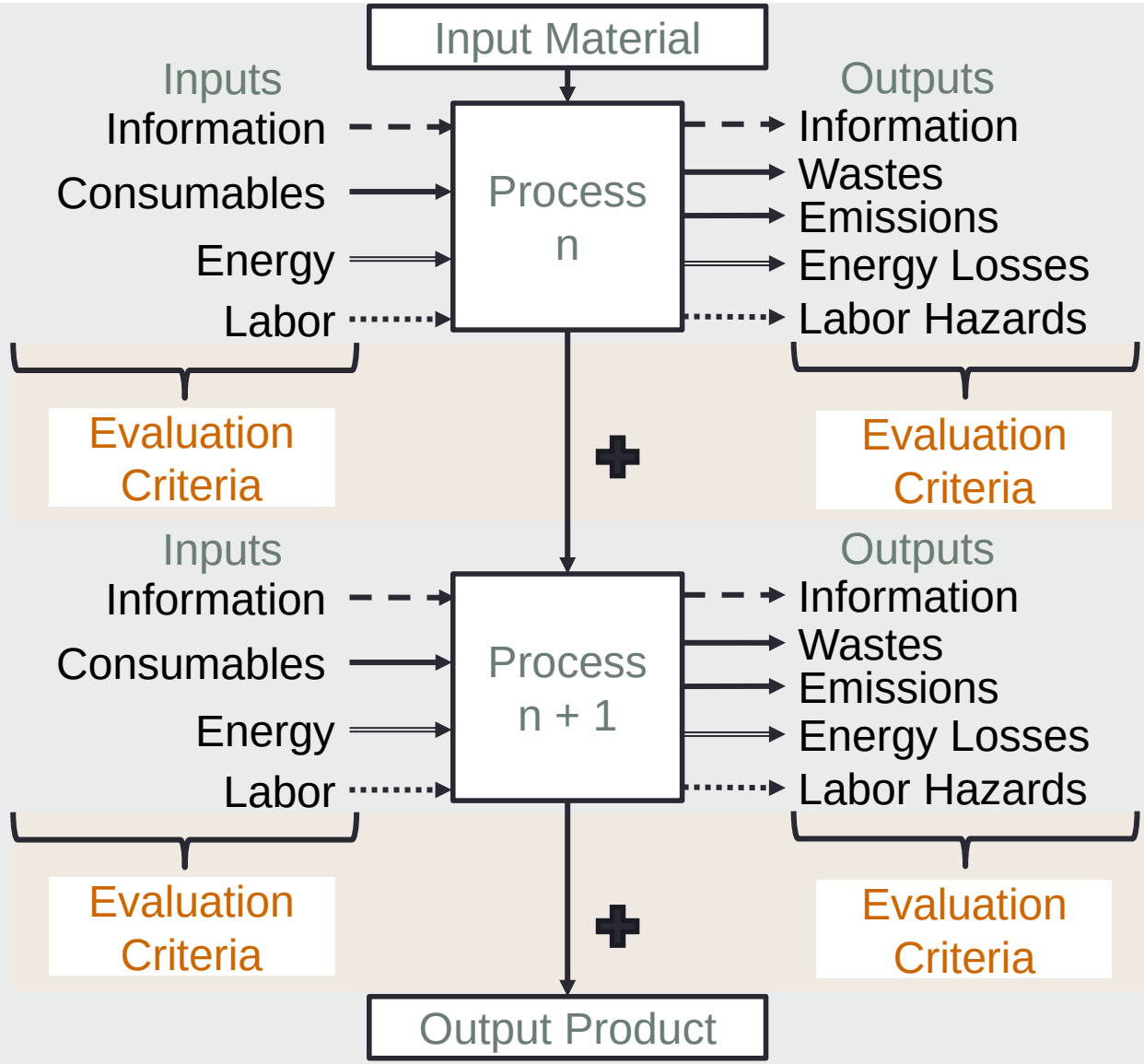


Adapted from: Gupta, Jayal, Badurdeen, Feng, Dilon, and Jawahir 2010. *A Framework of Product and Process Metrics for Sustainable Manufacturing*



Adapted from: Yuan, Li 2013. *Numerical Modeling of Specific Energy Consumption in Machining Process*

Setting the Context: Process Modeling



Adapted from: Garretson, Mani, Leong, Lyons, Haapala. *Characterization of Unit Manufacturing Processes and the Workpiece for Composable Analyses*

Manufacturing System Performance

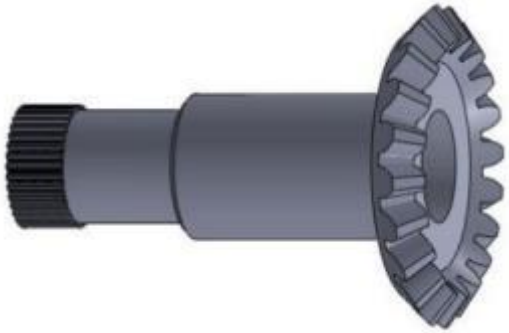
= Process Performance

+

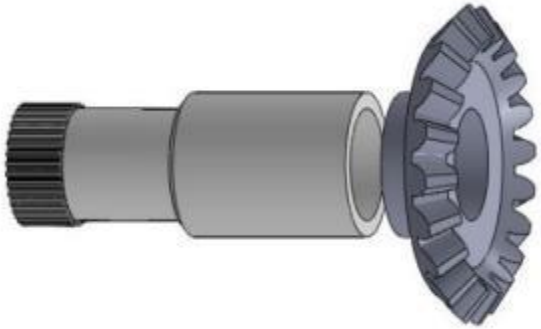
= Process Performance

Setting the Context: Sustainability and Cost

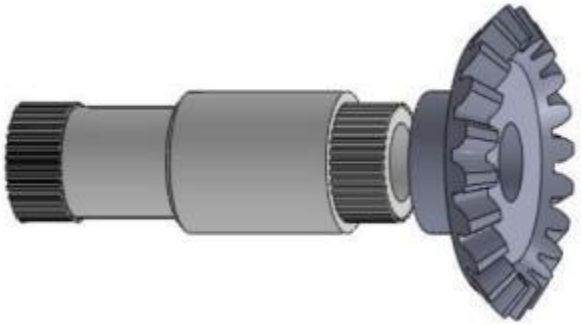
- Compare the sustainability performance of competing beveled gear designs



(1) Single component:



(2) Friction welded assembly:



(3) Mechanical joined assembly

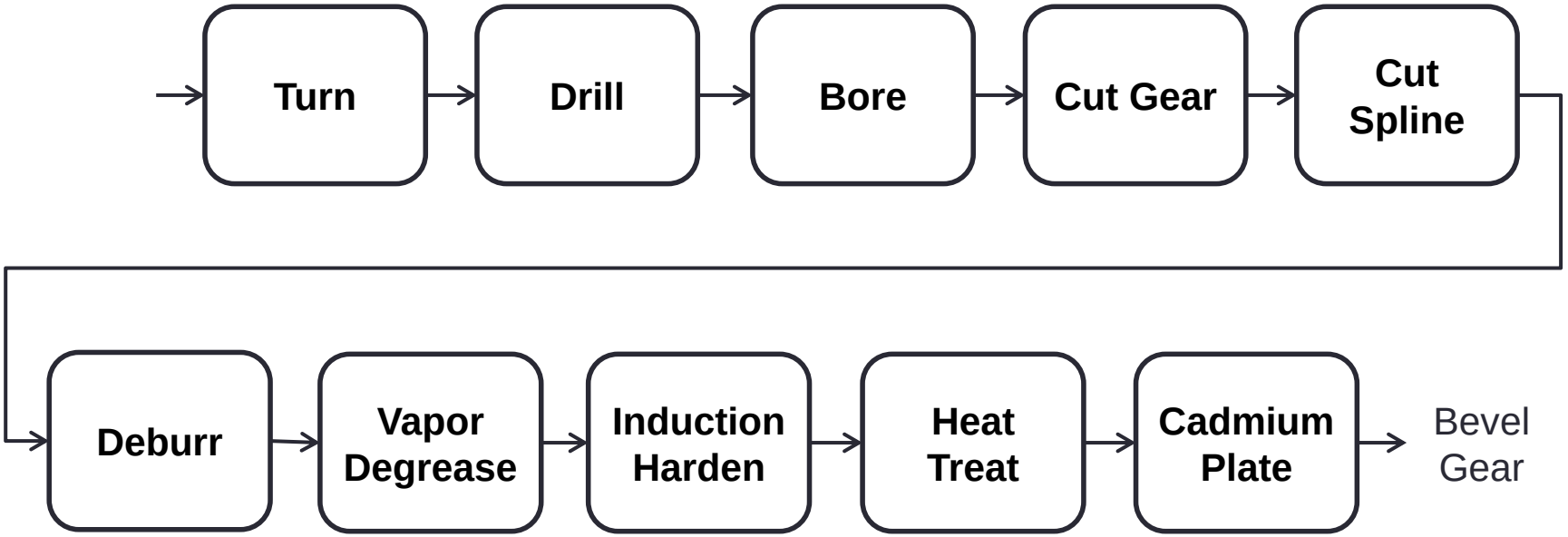
Setting the Context: Sustainability and Cost

- Selected a set of metrics and indicators

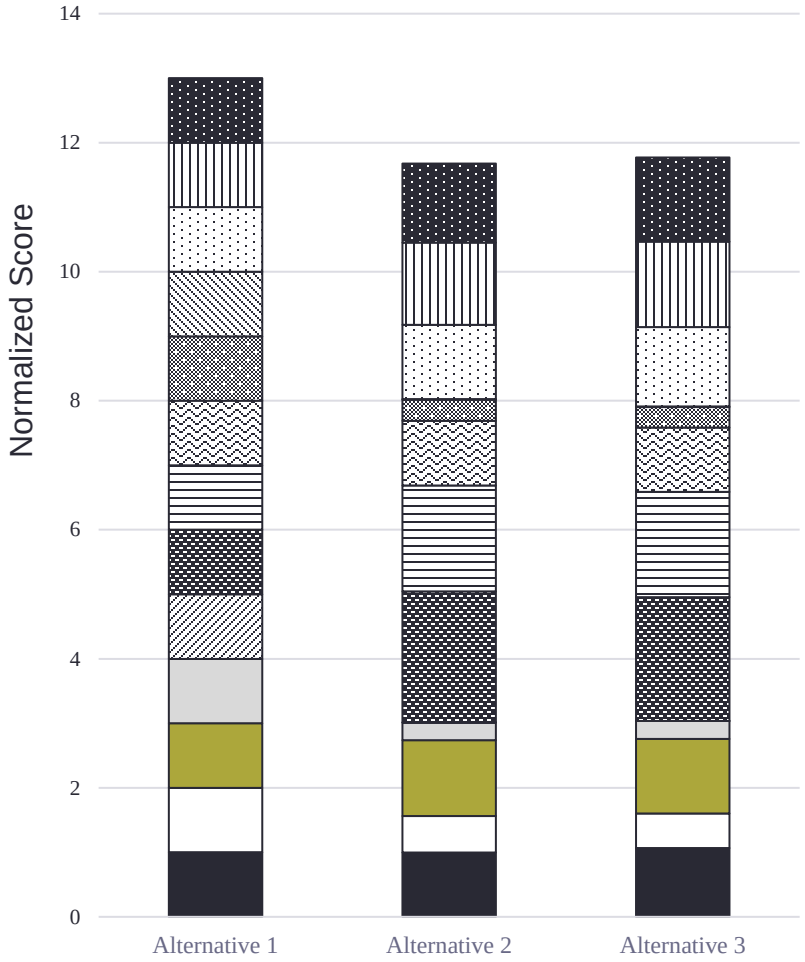
Performance Indicator	Performance Metric
Economic	Operating Cost
Materials	Input Material Non-Flyaway Content
Energy	On-site Energy Consumption
Water	Water Use
Liquid Effluents	Water Discharge
Emissions	GHG Emissions Pollutant Emissions
Waste	Waste to Landfill Waste to Recycle Hazardous Waste
Occupational Health & Safety	Acute Injuries Lost Work Days Chronic Illnesses

Setting the Context: Sustainability and Cost

- Created a Process Model

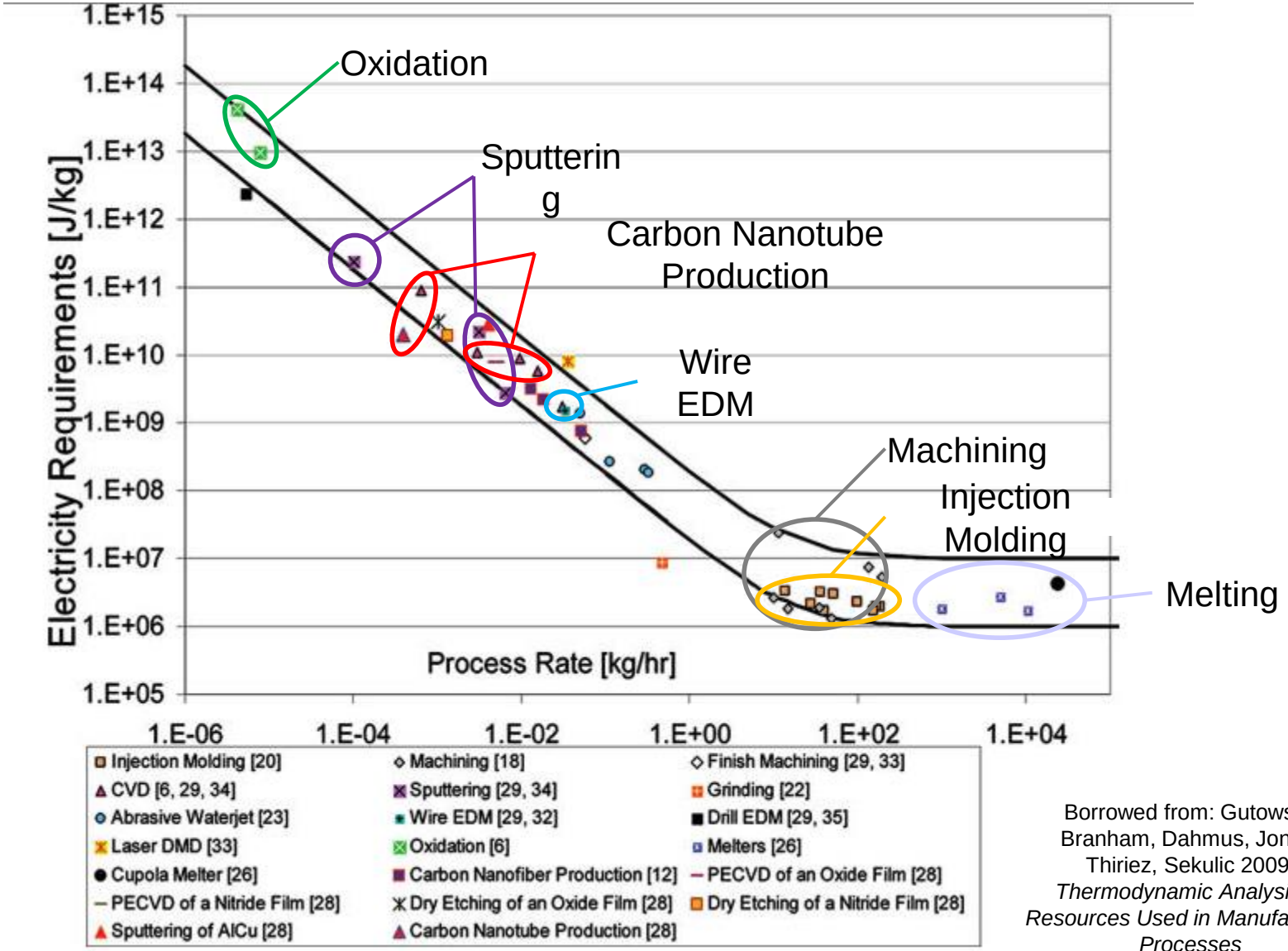


Setting the Context: Sustainability and Cost



- More sustainable to assemble or weld than to produce a single component
- Sustainability method identified previously overlooked areas for improvement

Setting the Context: Measurement Science



Borrowed from: Gutowski, Branham, Dahmus, Jones, Thiriez, Sekulic 2009. *Thermodynamic Analysis of Resources Used in Manufacturing Processes*

Focus Areas

- Manufacturing Metrics & Measurements
- Manufacturing Process Models

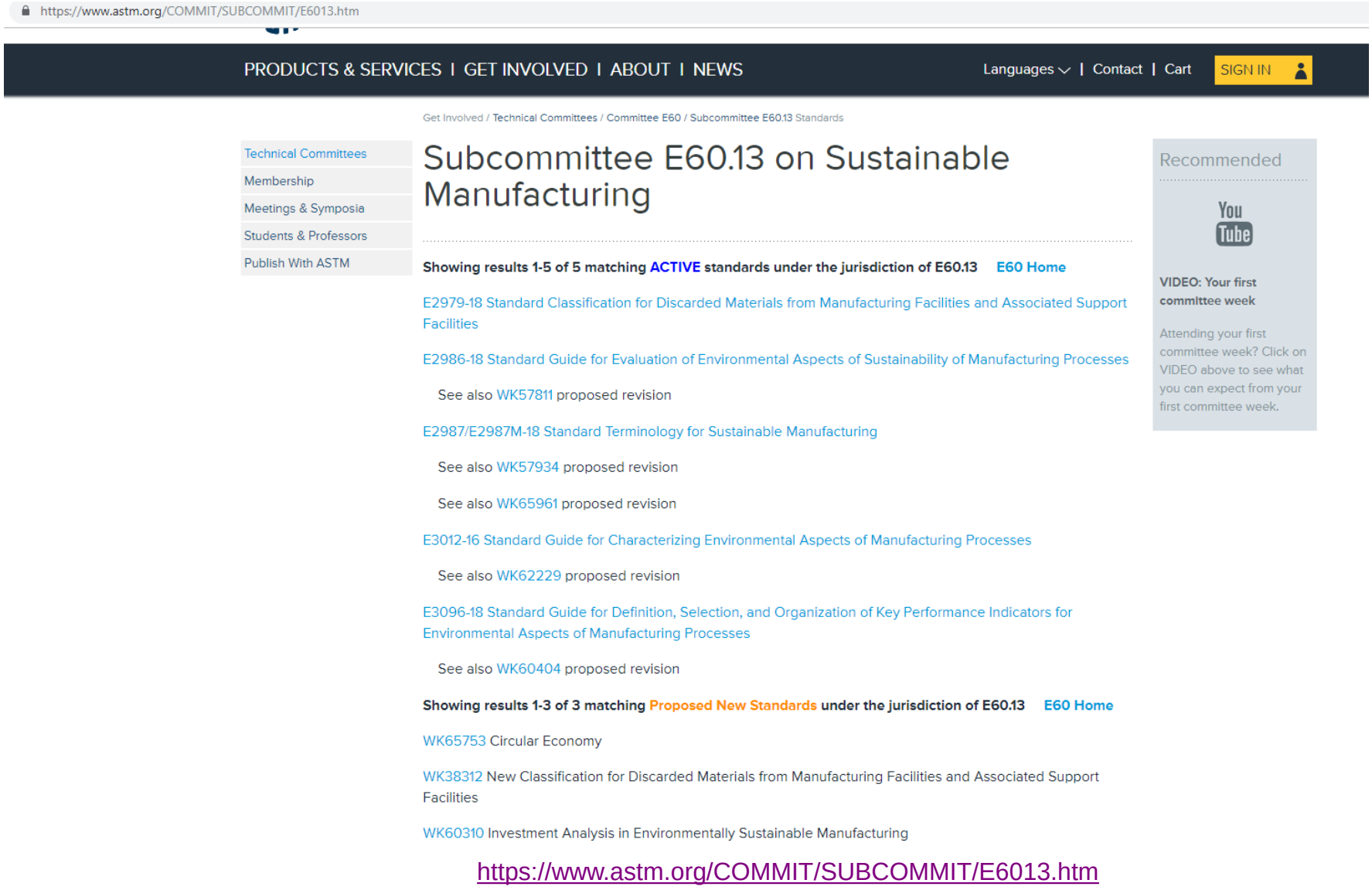
Metrics & Measurements

- What approaches do companies use to understand process-level issues and their effects on performance at the system-level?
- How are manufacturing performance indicators selected?
  - bottom up or top down
- What tools, methods, and systems are used to capture and track manufacturing-process level performance indicators?
  - How are measurements disseminated across decision makers

Manufacturing Process Models

- What is the value of modeling manufacturing processes?
  - What resources are available to investigate manufacturing processes?
- How does your company characterize individual manufacturing processes?
  - Input – Output – Control, capturing the process physics

Standards Overview – ASTM E60.13



https://www.astm.org/COMMIT/SUBCOMMIT/E6013.htm

ASTM E3012 – 16: Guide for Characterizing Environmental Aspects of Manufacturing Processes of Manufacturing Processes

This guide provides manufacturers a way to better characterize manufacturing processes and to systematically capture and describe sustainability information. This is accomplished by:

- providing a standardized and consistent method for graphically and formally describing manufacturing processes.
- defining Sustainability Characterization Methodology that assists in the construction of unit manufacturing processes (UMPs).
- defining four sets of attributes (inputs, outputs, product / process information, and manufacturing resources) that comprise the UMP model.

Impact:

- A formal information representation facilitates data exchange, sharing and communication with other manufacturing applications such as modeling and simulation.
- A formal information representation that enables new tool development to link manufacturing information and analytics, key for calculating sustainability performance measures.
- UMP models that enable interoperability between decision tools through the generation of process-specific data supporting standardized data and reference databases.

ASTM E2986-15: Standard Guide for Evaluation of Environmental Aspects of Sustainability of Manufacturing Processes

This guide:

- Provides a reference to the manufacturing community for the evaluation of environmental sustainability aspects of manufacturing processes. This guide is intended to improve efficiencies and consistencies of informal methods by providing procedures for consistent evaluations of manufacturing processes.
- Describes a procedure to identify parameters and models for evaluating sustainability metrics for a particular process. Users of this guide will benefit from insight into the sustainability implications of selected processes as well as the contributing factors.
- Sets boundaries for the evaluation of environmental sustainability of a process or processes,
- Identifies the process and equipment-related parameters necessary for environmental sustainability-driven process evaluation,
- Creates process models using these parameters,
- Utilizes process models to support consistent evaluations and sustainability-driven decision-making in a manufacturing enterprise.

Standards Usage

The following template is designed according to ASME standard E2986 -15. Where included, definitions originate from the aforementioned standard.

PROJECT GOAL

OBJECT or ACTIVITY

PERFORMANCE AREA

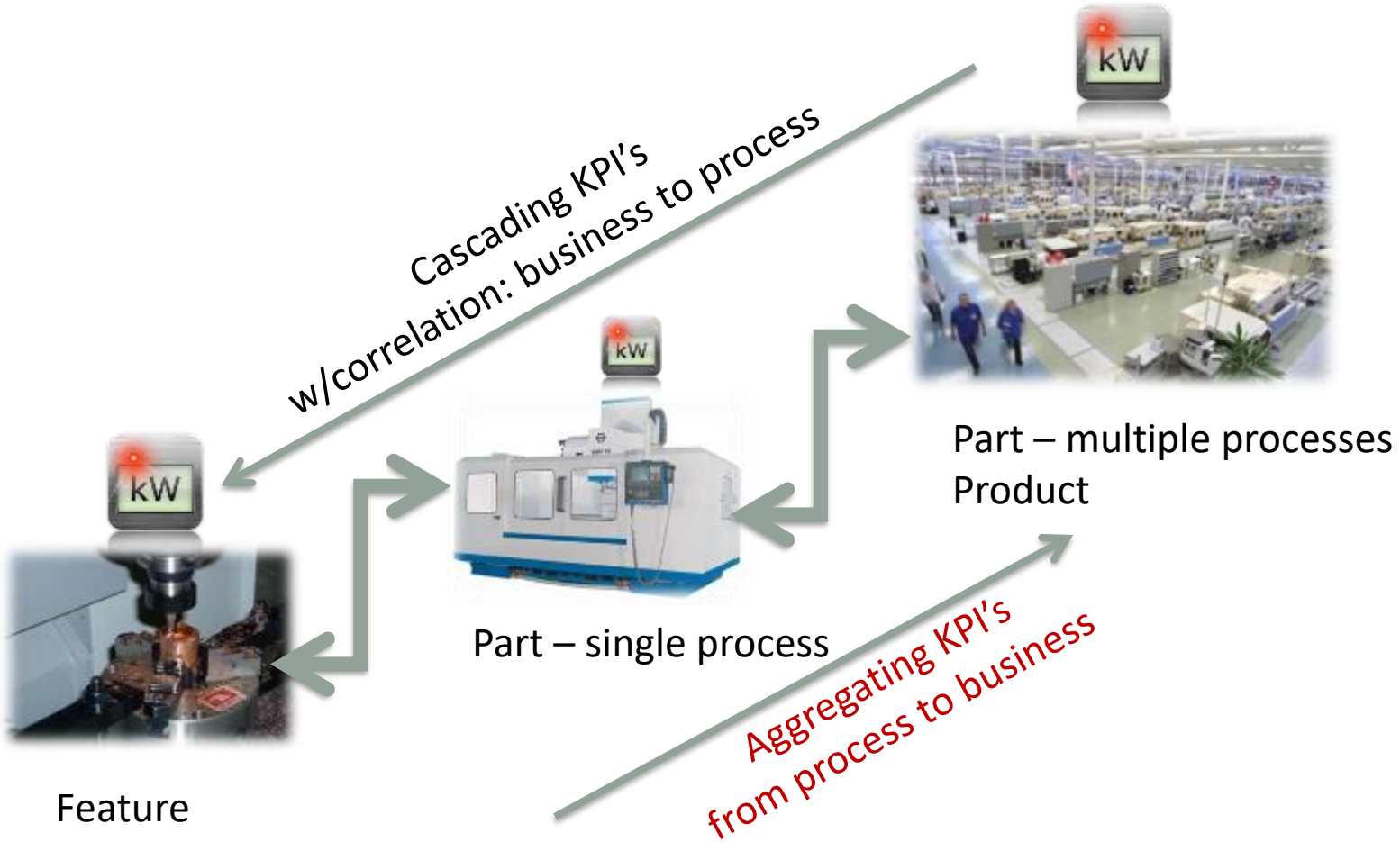
IDENTIFY INDICATORS

Indicators provide a context to measure, analyze, and score sustainability aspects of manufacturing processes. Indicators can be defined internally, or selected from various indicator repositories.

IDENTIFY PROCESSES

Process identification establishes the specific process or set of processes that contribute to the identified indicator.

What are the Right Metrics and How Do We Measure Performance at Various Levels?



Standards Usage Cont…

The following template is designed according to ASME standard E2986 -15.
Where included, definitions originate from the aforementioned standard.

IDENTIFY METRICS

Evaluation metrics associate the process or processes to be evaluated with the identified indicator. Metrics provide a measure for which indicators can be evaluated.

SET BOUNDARY CONDITIONS

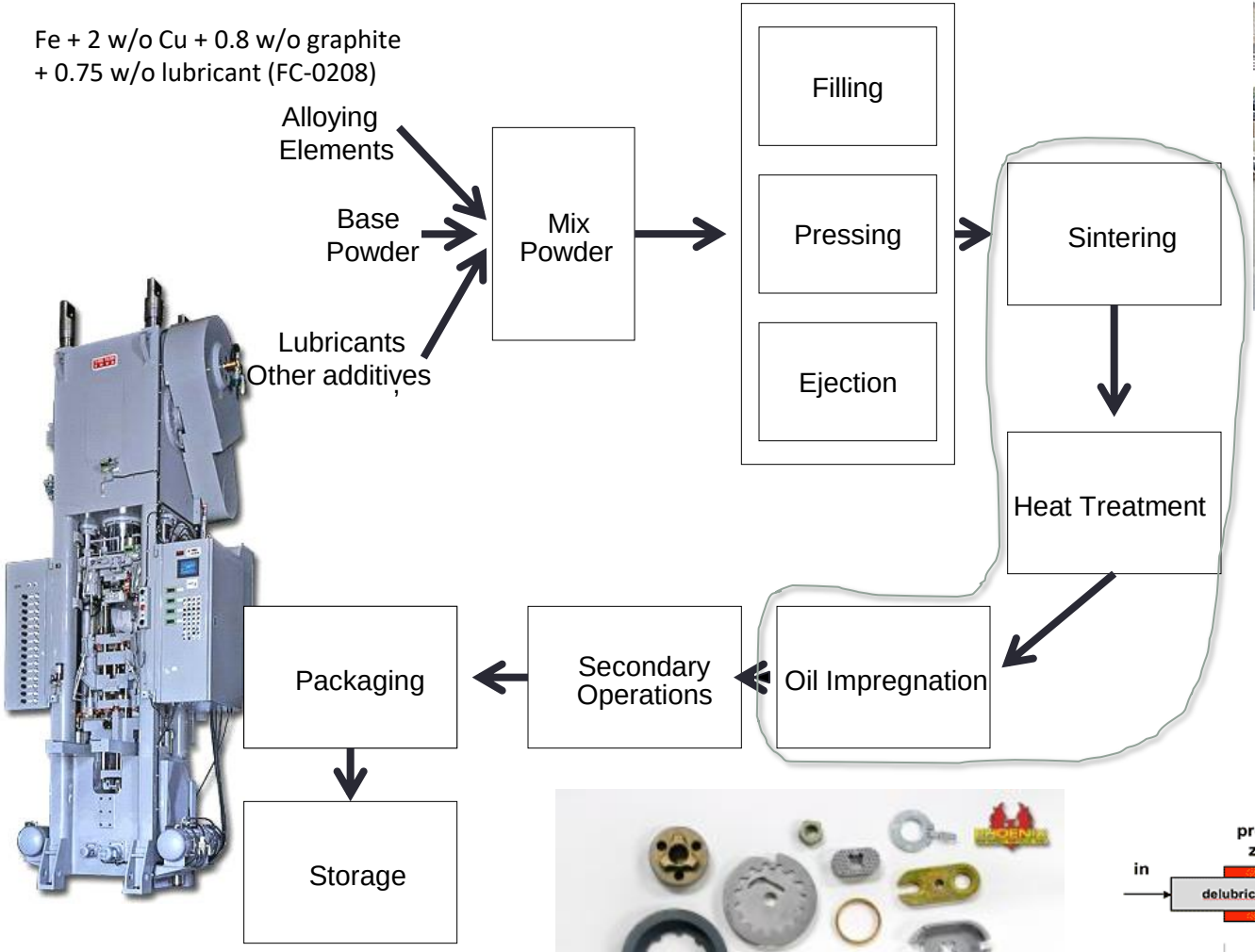
Boundary conditions limit the scope and constrain the extent of the evaluation. They may include the physical boundaries associated with identified equipment or time-related boundaries.

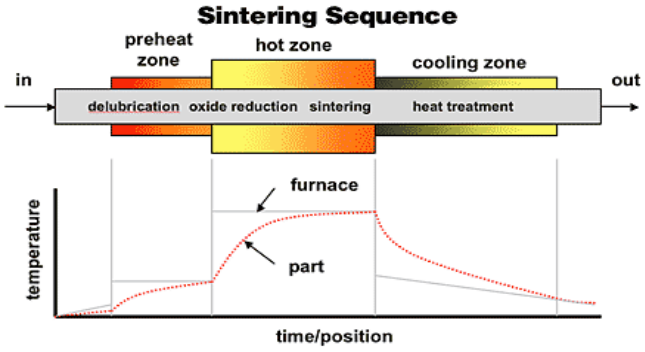
IDENTIFY INPUT AND OUTPUT PARAMETERS

Each unit manufacturing process has one or more input and output parameters associated with it. Input parameters are those parameters that feed into the process. Output parameters are those parameters that can be used to calculate the indicators used to evaluate manufacturing sustainability.

Powder Metallurgy Process/es

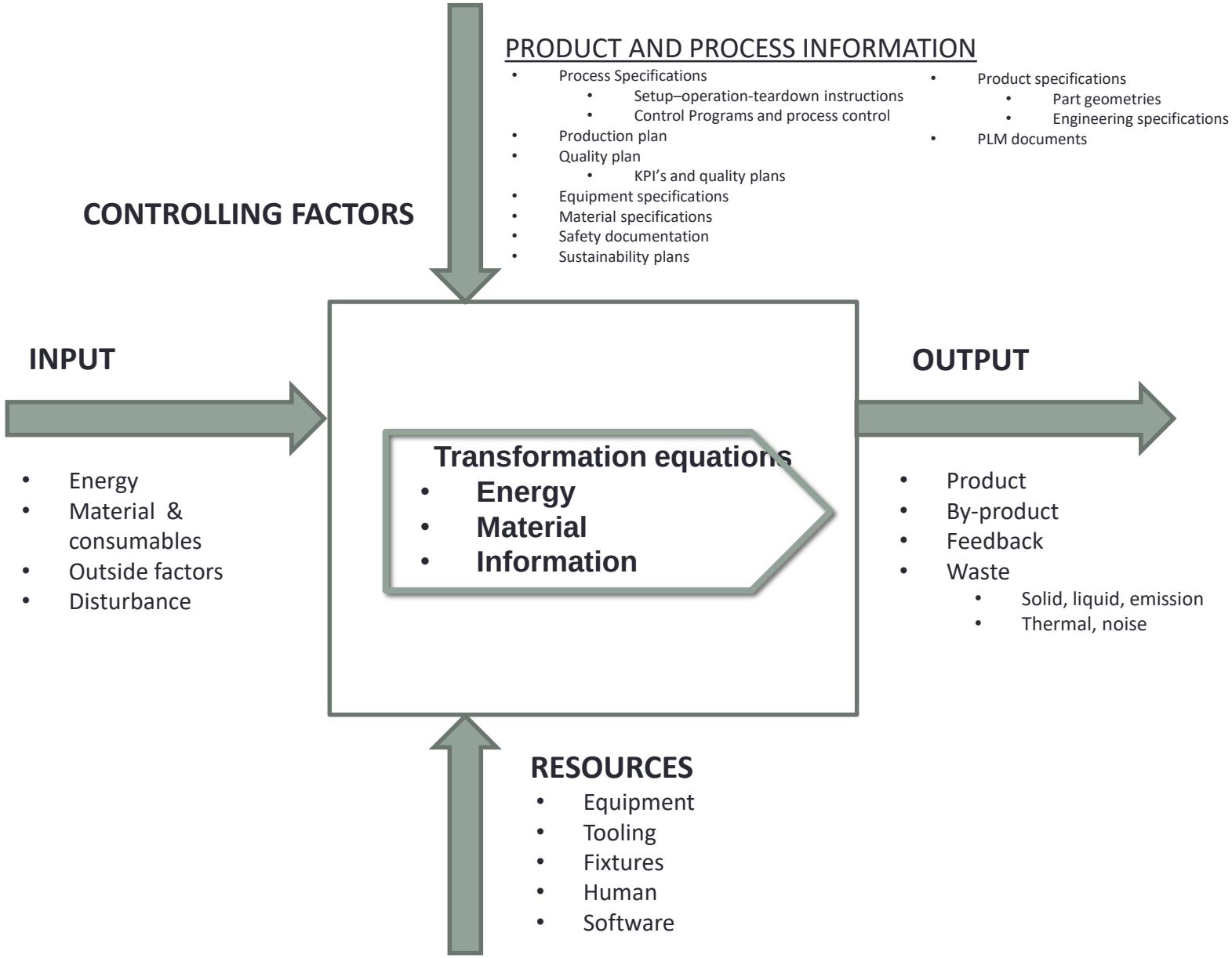
Fe + 2 w/o Cu + 0.8 w/o graphite
+ 0.75 w/o lubricant (FC-0208)





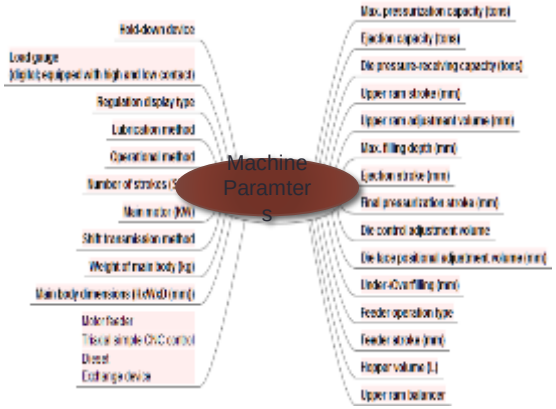
Advantage Sintered Metals, Inc

General Description of A Manufacturing Processes



Powdered Metal Process

Control Programs
Manuals, Dbases,
Procedures, CAD



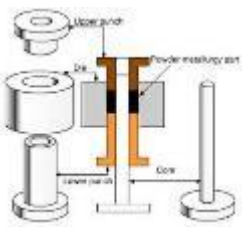
Scrap metal to Powdered Metal

Energy

Parts /by-products

Waste stream

- Spilled powder
- Heat
- Noise



Tooling and fixtures

Standards Usage Cont…

The following template is designed according to ASME standard E2986 -15.
Where included, definitions originate from the aforementioned standard.

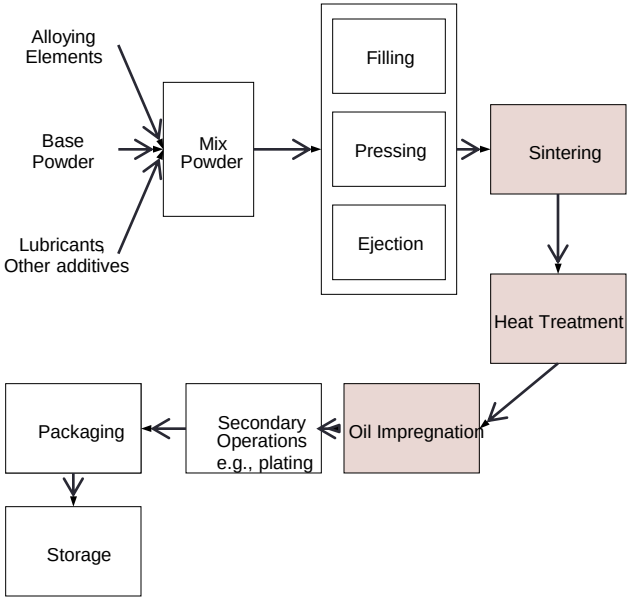
CREATE A PROCESS MODEL

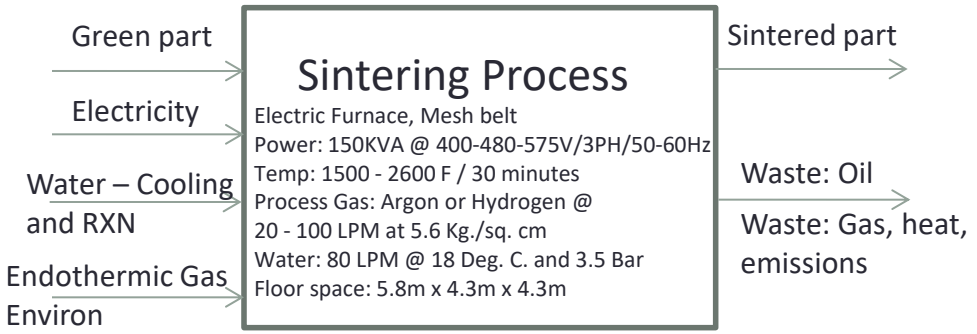
Process models are used to represent a process or set of processes. They can include the required analytics to support repeatable evaluations of a manufacturing process.

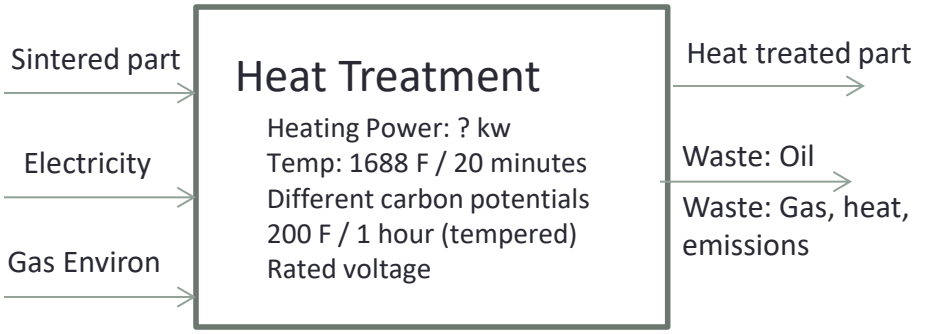
IDENTIFY RESOURCES REQUIRED TO EVALUATE YOUR PROJECT

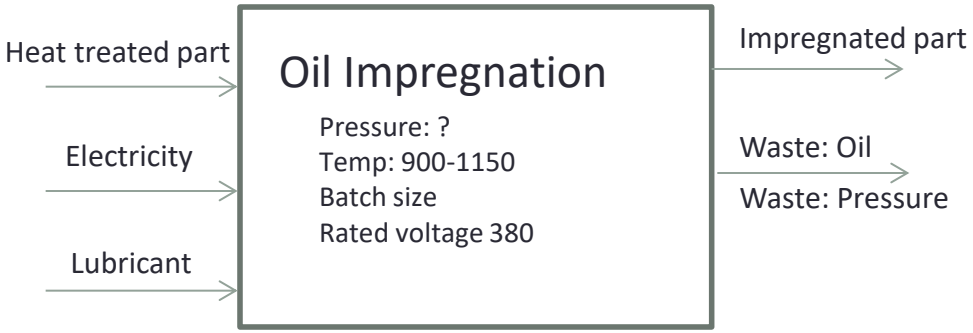
Equipment, manufacturing applications, services, and personnel

Creating a process model









Assignment

Choose any production process to demonstrate the application of generalized Unit Manufacturing Process (UMP) representation for purposes of sustainability assessment.

- Use the following as guideline for the document
- Project goal
- Object or activity
- Performance area
- Identify indicators
- Identify processes
- Identify metrics
- Set boundary conditions
- Identify input and output parameters
- Create a process model
- Identify resources required to evaluate your project

Page Limit: 10 pages