Economic and environmental sustainability of manufacturing processes

Strumenti dell'Ingegneria per l'Industria 4.0

A.Y. 2017-2018

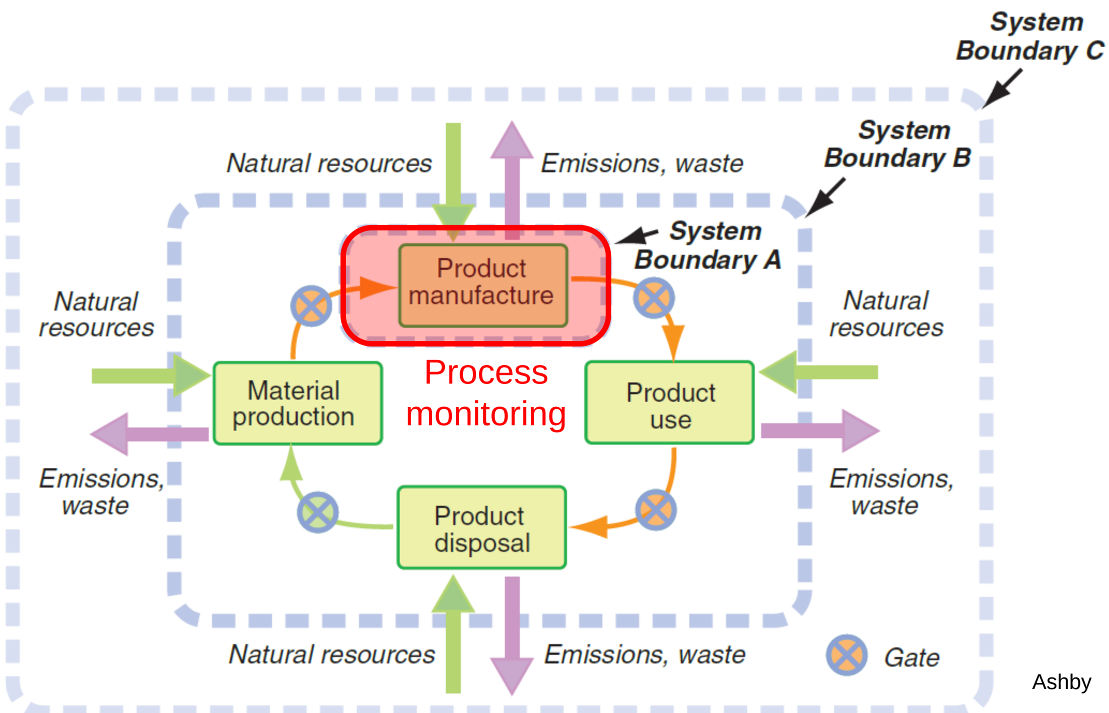
Paolo C. Priarone, Luca Settineri

Politecnico di Torino DIGEP

Process monitoring

If you cannot measure it, you cannot improve it.

Lord Kelvin



Ashby

Critical flows in manufacturing

- Critical flows of interest for manufacturing processes include electrical energy, cutting fluid, compressed air, water, and solid process waste.

- These flows can be divided into two categories of generalized flows:

- Electrical flows (electrical energy)
- Fluid flows (cutting fluid, compressed air, and water).

- Material and solid process waste flows are not listed, not because they are insignificant, but because they are normally considered as part of the standard analysis.

Critical flows in manufacturing

- The relative importance of such flows can be determined based on the physics of the manufacturing process.

Process type	Process mechanics	Critical flows
Metal cutting	Shearing (i.e., removal) of material across a sharpened edge	Electrical energy, water, oils, compressed air, solid waste, liquid waste, cutting tools
Metal forming	Reconfiguration (i.e., conservation) of material by volumetric and geometric changes to the bonding structure	Electrical energy, water, oils, solid waste, liquid waste, dies
Lithography	Formation (i.e., addition) of material layer by selective UV exposure	Electrical energy, water (DI), solid waste, liquid waste, hazardous waste, chemicals (photoresist, solidifying agents, adhesion promoters, etc.), lenses, UV light sources, masks, various gases (to fuel ovens)

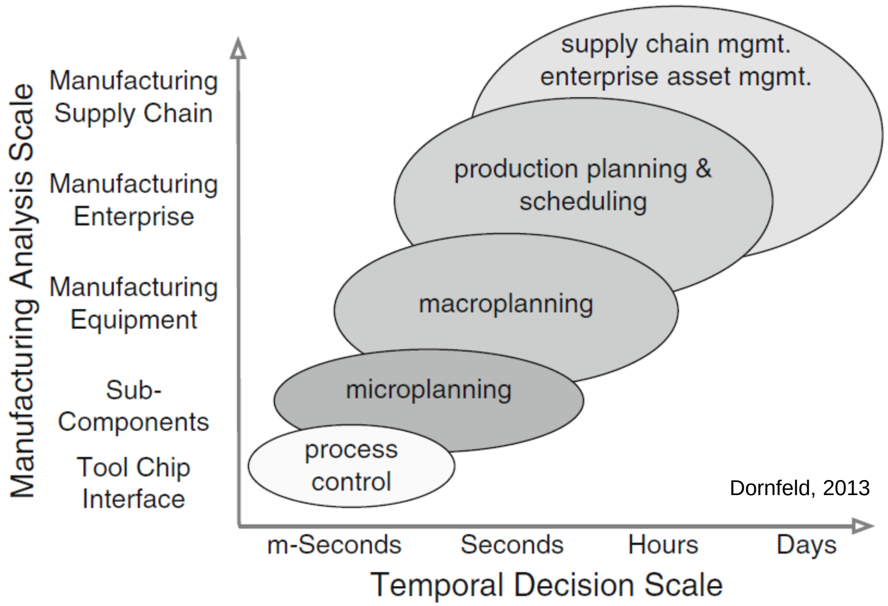
Dornfeld, 2013

From monitoring to desision making

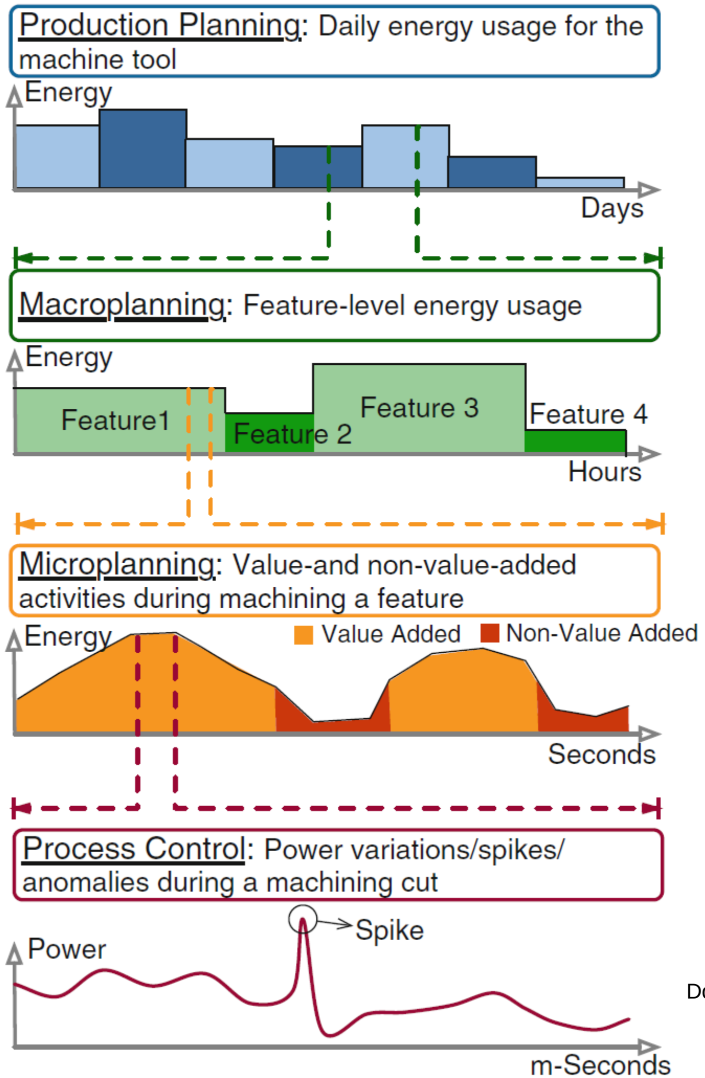
- Sensors can be applied in characterizing the various flows that determine the environmental impact of a manufacturing process.
- *Quaere*: How to apply process monitoring to decision making processes?

- Manufacturing systems can be studied at different levels of analysis, ranging from that of the entire enterprise to the tool-chip interface.

- Each of these levels also has a corresponding temporal scale of decision making, which ranges from several days at the enterprise level to microseconds at the tool-chip level.



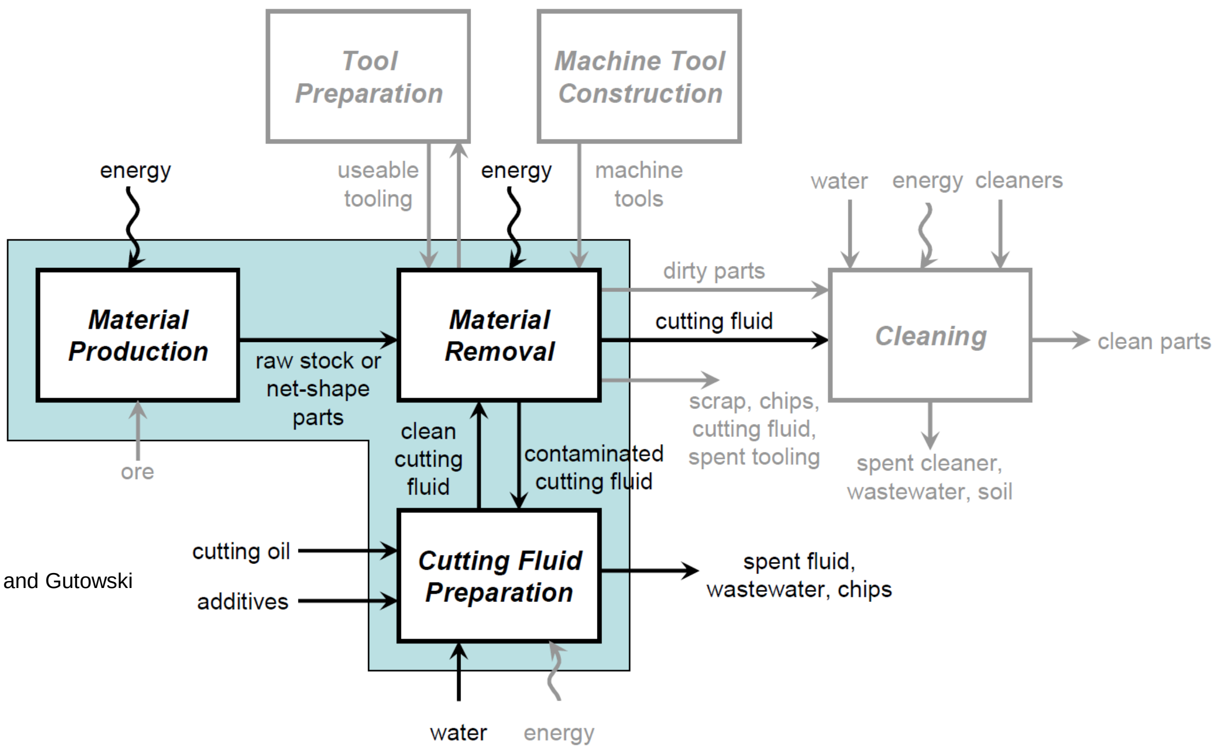
From monitoring to desision making



Dornfeld, 2013

Case study: machining

- System-level environmental analysis of machining.
- Boundaries: the overall system includes activities such as tool preparation, material production, material removal, and cleaning.
- Environmental impact of the material removal process
  + impact of associated processes.



Dahmus and Gutowski 2004

Machining Material removal

- Most of the environmental impact from the material removal process stems from energy use.

- In estimating the energy requirements for material removal, *specific cutting energies* (as a function of workpiece's material properties, presence of cutting fluids, type of tool, etc.) are often used.

- The specific energy requirement is far from the total energy required in actual production. In production machining, in addition to providing energy to the tool tip, *additional energy* must be provided to power auxiliary equipment such as:
  - workpiece handling equipment,
  - cutting fluid handling equipment,
  - chip handling equipment,
  - tool changers,
  - computers,
  - machine lubrication systems.

Machining Case study

- *Case study*: development of an energy consumption monitoring procedure for machine tools (Behrendt et al., 2012) .

- Aim: measure and compare the power consumption of nine machine tools:

  - four 3-axis vertical milling machines
    Mori Seiki (MS) NVD1500 (24,000 and 40,000 rpm)
    MS Dura Vertical (DV) 5060
    Haas VF-0;
  - a 4-axis horizontal milling center (MS NH8000);
  - two 5-axis vertical milling machines (MS NMV1500 and MS NMV5000);
  - a mill-turn center (MS NT1000);
  - a CNC lathe (MS NL200SY).

Machining Case study

Behrendt et al. 2012

- Standby power
- Component power

  process-induced power demand: spindle, axis and woorkatble jog, pumps, etc.

- Machining power

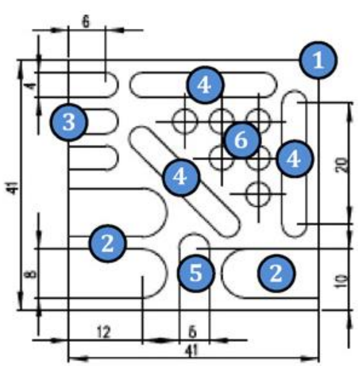
  same part,

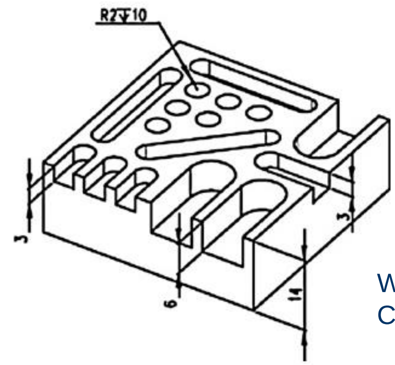
  3 sizes:

  small

  medium

  large



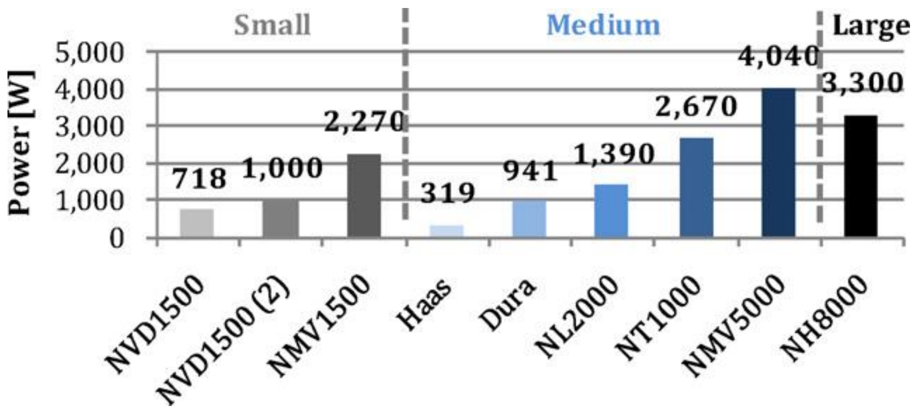


Workpiece:
Cold rolled AISI/SAE 1018 steel

Operation #	1	2	3	4	5	6
DOC [mm]	1.0, 2.0, 3.0					20.0
Feed rate [mm/min]	160	200	400	400	400	100, 200, 300, 400, 500, 600
		240	480			
		280	560			
Feed/tooth [mm/tooth]/feed/revolution [mm/rev]	0.05	0.05	0.05	0.05	0.05	0.05, 0.1, 0.15, 0.2, 0.25, 0.3
		0.06	0.06			
		0.07	0.07			

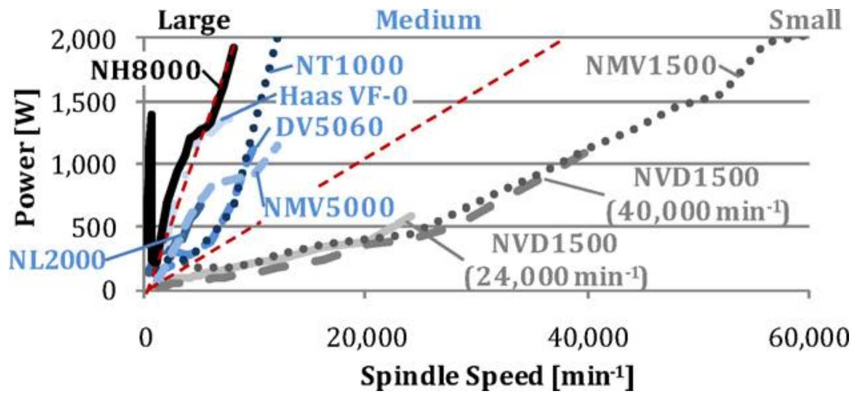
Machining Case study

- Standby power:



- Component power

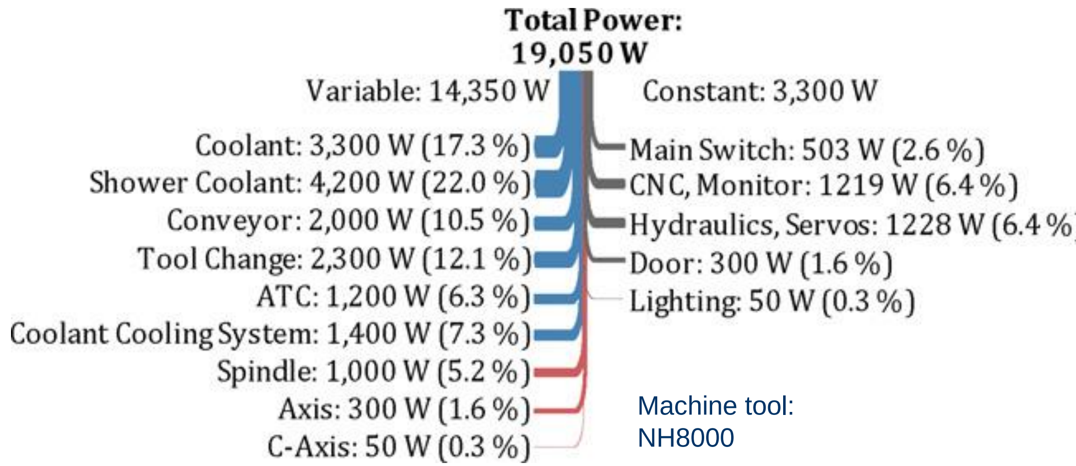
Spindle:



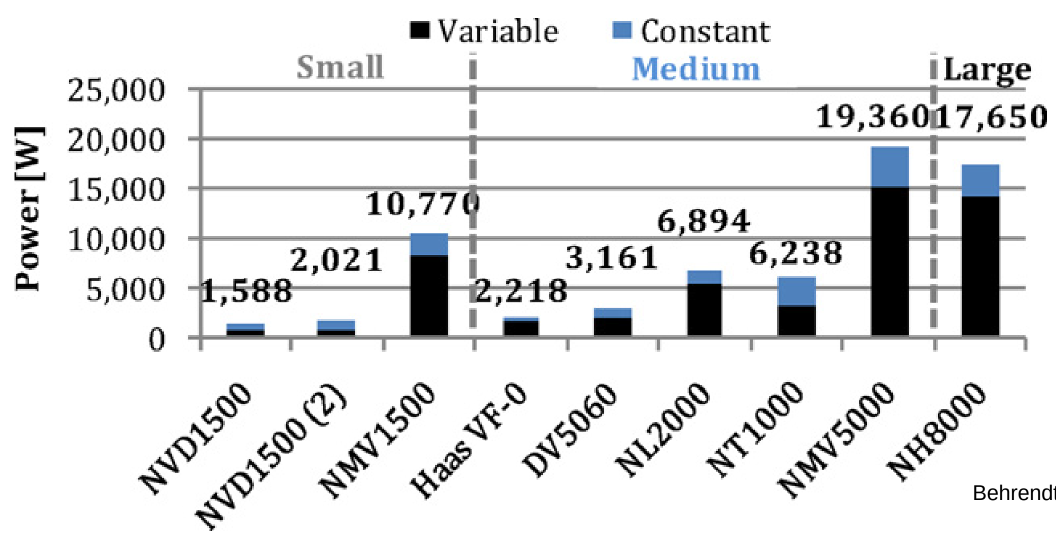
Behrendt et al. 2012

Machining Case study

- Component power



Machine tool:
NH8000



Behrendt et al.
2012

Machining Case study

- Machining power

Behrendt et al. 2012

Characteristics of machining process.

Value	Small		Medium		Large	
	NVD1500	NMV1500	Haas VF-0	DV5060	NMV5000	NH8000
T_{Cycle} [h]	0:10:45		0:15:00		1:16:15	
E [kWh]	0.1845	0.7142	0.3638	0.5557	1.9323	9.2907
q_{Cut} [%]	3.65	1.85	20.53	14.7	4.25	7.57
P_{Peak} [W]	3320	20,130	15,610	16,440	36,900	55,600
PF [%]	98	64	66	69	51	69

- NVD1500 used 0.19 kWh for machining the small test piece, while the NH8000 used 9.3 kWh for the large test piece.
- The energy that is used for the cutting process only (E_{Cut}) is given as a percentage of total energy E (q_{Cut}), that ranges between 2% and 20%.
- For the complex machines, however, this value accounts for only 2–8%.
- This observation shows the little impact contributed by the machining process.

Machining (2) Material production

- The production of materials from stock and feeds are energy- and resource-intensive processes. While material production may seem to be outside the system boundaries of machining, machining can be viewed as a *process that pulls in raw materials, altering them in the course of producing products.*

- Thus, the energy requirements of the raw materials should be examined.

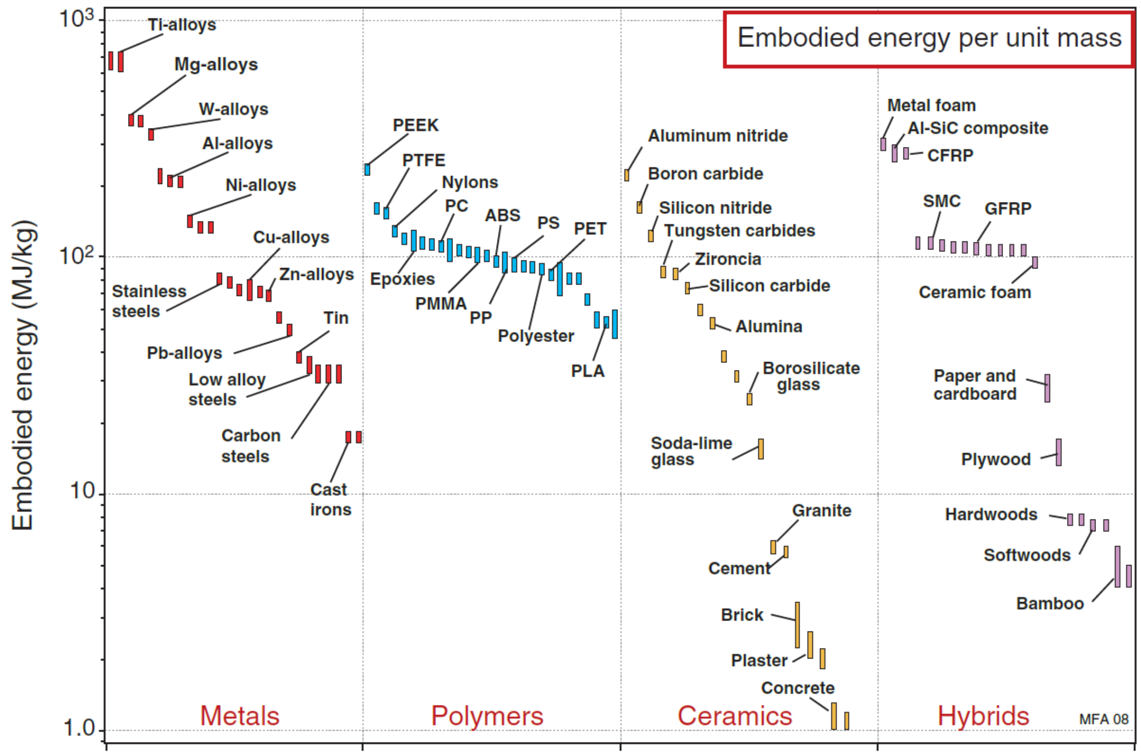
- In creating products, machining often uses *large amounts of material*. In many cases, only a fraction of the total material entering into the manufacturing plant leaves in the form of a product.

- Estimates of *scrap production* in machining range from 10% to 60%.

- *Recycling* is an important process requirement that must be considered.

Machining (2) Material production

- *Embedded energy: the energy per unit mass consumed in making a material from its ores and feedstock*
- Material production is also important to consider due to *other environmental implications*. I.e. metal smelting can result in sulfur dioxide emissions, heavy metal emissions, and particulate emissions, all of which have serious local and global effects on the environment.



Ashby 2012

Machining (3) Cutting fluid preparation

- Cutting fluids are used in machining processes for cooling and lubrication purposes, since the reduction in cutting temperatures increases tool life.
- On the other hand side, cutting fluids negatively affect the environmental impact of a process.
- As an example, common soluble oils are highly diluted in water, nevertheless the 5% (by volume) of the cutting fluid is a mixture of oil, emulsifiers (as sodium sulfonate, nonylphenol ethoxylates, PEG esters), and additives (as calcium sulfonate, alkanoamides, and blown waxes).
- Many chemical additives are pollutant for the environment, as well as hazardous substances for workers' health.
- Exposures to the airborne particles of the mist consequent to cutting fluid vaporization might lead to occupational diseases.

Metalworking Fluid Sales (1990)	
Total sales volume	97 million gallons/year
Metalworking Machines (1989)	
Total metalworking machines	1.871 million machines
Cutting machines (inlcudes milling, turning, sawing, and drilling)	1.394 million machines
Percentage of Cutting machines	75%
Grinding machines	0.435 million machines
Percentage of Grinding machines	23%
Non-traditional machines	0.042 million machines
Percentage of Non-traditional machines	2%
Cutting and Grinding Machines	1.829 million machines
Concentrated Metalworking Fluid Use (without water)	
Metalworking Fluid used per Cutting Machine	53 gallons/machine/year
Total Metalworking Fluid for all Cutting machines	74 million gallons/year
Diluted Metalworking Fluid composition (with water)	
Percentage of Metalworking Fluid	5%
Percentage of Water	95%
Total Water for all Cutting Machines (without evaporative losses)	1405 million gallons/year
Evaporative losses	1%
Evaporative replacement	14 million gallons/year
Total Water for all Cutting Machines	1419 million gallons/year
Water used per Cutting Machine	1018 gallons/machine/year
Work Scenario	
Work days per year	250 days/year
Daily Use	
Daily Metalworking Fluid used per Cutting Machine (concentrated)	0.21 gallons/machine/day
Daily Water used per Cutting Machine	4.07 gallons/machine/day

Dahmus and Gutowski 2004

Machining (4) Cutting tool production

- While tooling plays a major role in the machining process, *the direct environmental impact of tooling is limited*.
- Producing tools does require some energy-intensive materials and processes. Tungsten, with an embodied energy of approximately 400 MJ/kg, comprises most of the mass of carbide cutters. Some of the manufacturing steps, including sintering, which is used to form the carbide tool, and physical vapor deposition (PVD) or chemical vapor deposition (CVD), which is used to coat the carbide, are also quite energy intensive, with estimates on the order of 1 to 2 MJ per process per cutting insert.
- Due to their relatively long life, the environmental cost of tools and tool maintenance is often amortized over numerous products, thereby making the environmental impact relatively insignificant on a per part basis.
- However, the effect of tool materials on allowable cutting speeds, and thus on material removal rate, should not be overlooked. Selection of appropriate tools can allow for increased material removal rates, thereby reducing the total machining energy required.

Machining (5) Machine tool costruction

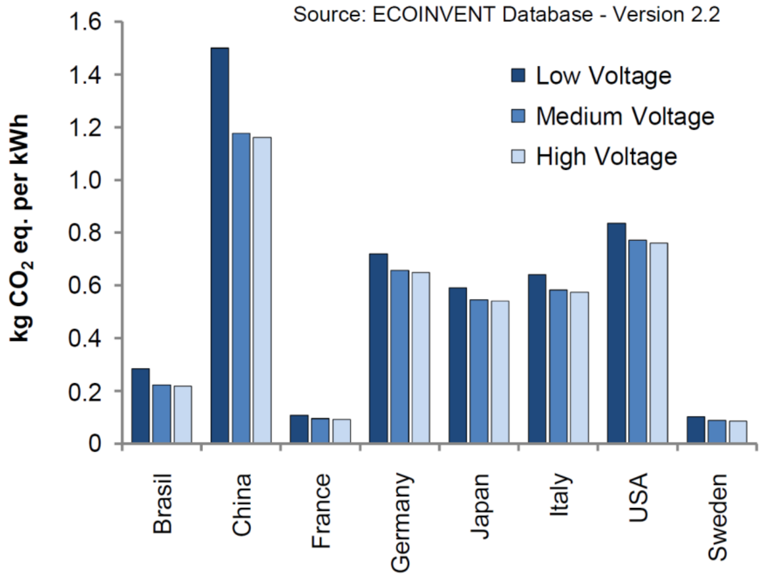
- Like tooling, the *direct* environmental impact of machine tools is limited.
- Most machine tools are in use for many years.
- These long lifetimes mean that the environmental impact of machine tool construction is amortized over numerous products over many years.
- Thus, the environmental impact per part is relatively small.
- The larger effect of machine tools on machining has to do with *energy efficiency*.
- Newer machine tools can be significantly more energy-efficient than older machine tools, resulting in energy savings during material removal.

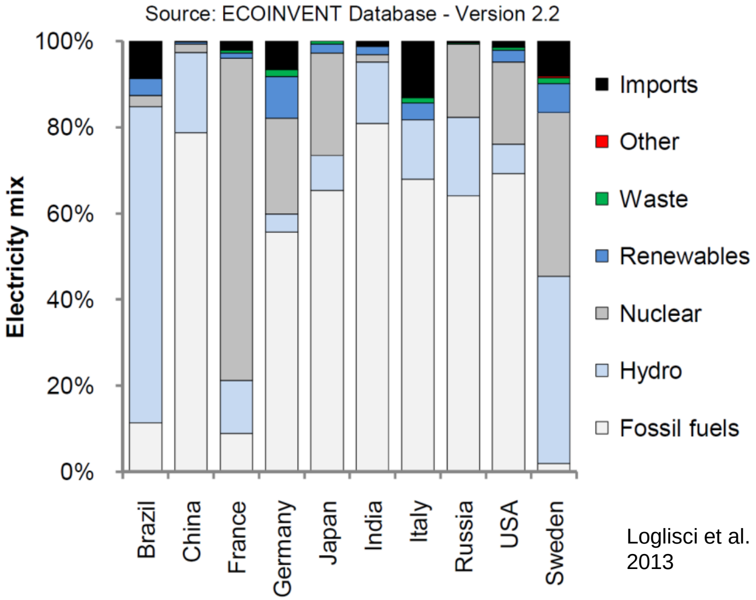
Machining (6) Cleaning

- Of the processes that play a role in machining, cleaning is one of the most often cited when discussing environmental impact.
- The importance of cleaning and its environmental impact are highly dependent on the product being made.
- High-end painted products must often undergo multiple cleaning steps, while other products might be acceptable with a simple rag wipe down.
- This highly diversified cleaning landscape, both in terms of amount of cleaning and type of cleaning, make *general qualitative analysis* of this process difficult.

Machining: keypoints

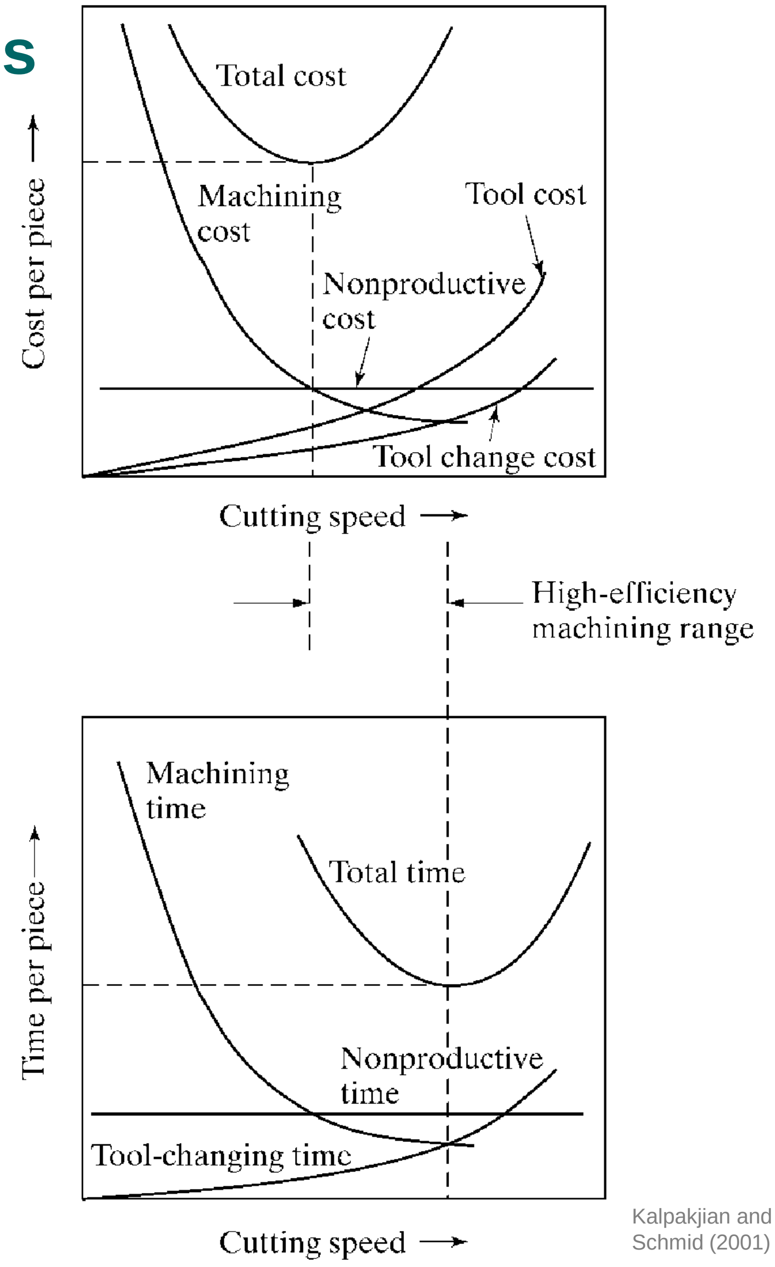
- The analyses of the (1) material removal and (2) material preparation processes, focus heavily on energy use.
- Energy use and energy sources are important to examine when investigating environmental impacts.
- In the case of the material removal process, the energy for this activity comes from electricity from the power grid.
- The environmental concerns associated with (3) cutting fluid preparation and (6) cleaning are tied more closely to liquid and hazardous waste.





Loglisci et al. 2013

Design of machining processes

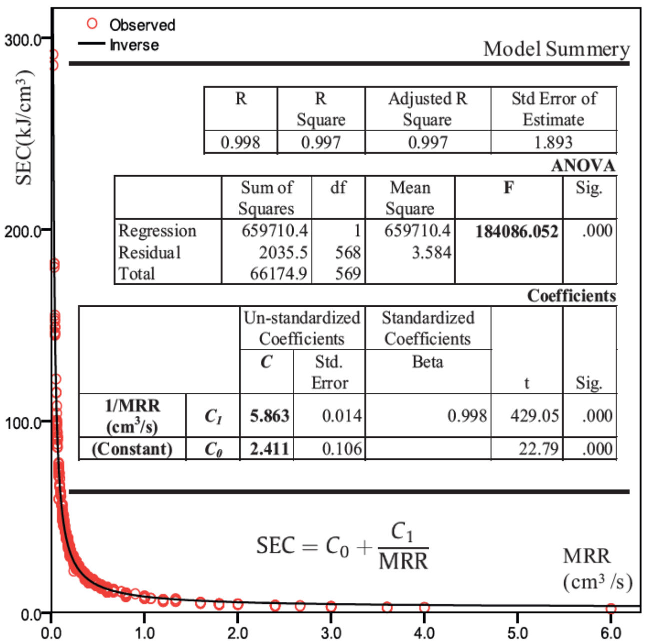


Kalpakjian and Schmid (2001)

- Time- and cost-based optimization models are conventionally applied for machining.
- The process parameters allowing for the maximum productivity or the minimum cost can be easily identified.

Design of machining processes

- In recent years, energy- and resource-efficiency optimization criteria have gained an increasing interest, at different level of analysis.
- Black box vs. bottom-up approaches for machining.



Model Summery

R	R Square	Adjusted R Square	Std Error of Estimate
0.998	0.997	0.997	1.893

ANOVA

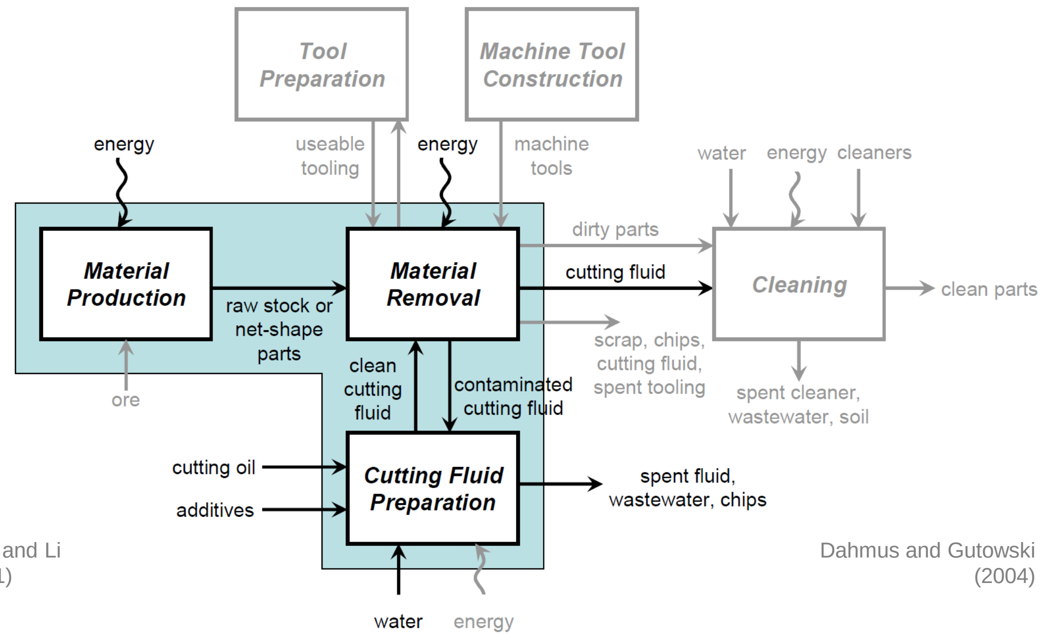
	Sum of Squares	df	Mean Square	F	Sig.
Regression	659710.4	1	659710.4	**184086.052**	.000
Residual	2035.5	568	3.584		
Total	66174.9	569			

Coefficients

		Un-standardized Coefficients C	Un-standardized Coefficients Std. Error	Standardized Coefficients Beta	t	Sig.
1/MRR (cm^3/s)	C_1	**5.863**	0.014	0.998	429.05	.000
(Constant)	C_0	**2.411**	0.106		22.79	.000

$$SEC = C_0 + \frac{C_1}{MRR}$$

Kara and Li (2011)



Dahmus and Gutowski (2004)

Design of machining processes

- Bottom-up approach
- Four process metrics:
  - process time, *t (s)*
  - process cost, *C (€)*
  - primary energy demand, *E (J)*
  - carbon dioxide emissions, *CE (kg)*

$$Metric = \sum_{i=1}^{n} Contribution_i$$

- ✓ *Direct* and *indirect* contributions
- ✓ System boundaries

Process Metric	*Contributions due to machine tool usage*			*Other indirect contributions*			
	Setup	Cutting	Tool change	Cutting tool	Workpiece	Lubricoolant	Cleaning
t (s)	t_1	t_2	$t_3 \cdot t_2/T$	-	-	-	t_4
C (€)	C_1	C_2	C_3	C_4	C_5	C_6	C_7
E (J)	E_1	E_2	E_3	E_4	E_5	E_6	E_7
CE (kg)	CE_1	CE_2	CE_3	CE_4	CE_5	CE_6	CE_7

Design of machining processes

Process metric → Specific process metric

- Total production cost, *C* (€)

$$C=\overbrace{\overbrace{\left(h_c+x_{EL}\cdot P_{\text{stb}}\right)\cdot t_1}^{C_1}+\overbrace{\left(h_c+x_{EL}\cdot P\right)\cdot t_2}^{C_2}+\overbrace{\left(h_c+x_{EL}\cdot P_{\text{stb}}\right)\cdot t_3\cdot\frac{t_2}{T}}^{C_3}}^{\textit{Machine tool use related costs}}+\overbrace{\overbrace{x_{TE}\cdot\frac{t_2}{T}}^{C_4}+\overbrace{x_W\cdot V_W}^{C_5}+\overbrace{x_L\cdot q_L\cdot t_2}^{C_6}+\overbrace{x_{CL}\cdot V}^{C_7}}^{\textit{Ancillary costs}}$$

- Specific production cost, U_C (€/mm^3)

$$U_C=\frac{C}{V}=\frac{\left(h_c+x_{EL}\cdot P_{\text{stb}}\right)\cdot t_1}{V}+\frac{h_c+x_{EL}\cdot P}{\text{MRR}}+\frac{\left(h_c+x_{EL}\cdot P_{\text{stb}}\right)\cdot t_3\cdot\left(\frac{1}{T}\right)}{\text{MRR}}+\frac{x_{TE}\cdot\left(\frac{1}{T}\right)}{\text{MRR}}+\frac{x_W\cdot V_W}{V}+\frac{x_L\cdot q_L}{\text{MRR}}+x_{CL}$$

Where (for longitudinal turning operations):

$$\text{MRR}=\pi\cdot\frac{D_i^{\,2}-D_f^{\,2}}{4}\cdot\frac{f\cdot v_c}{\pi\cdot D_{avg}}\cdot\frac{1000}{60}=a_p\cdot f\cdot v_c\cdot\frac{1000}{60}\qquad T=\frac{A}{v_c^{\,1/\alpha}\cdot f^{\,1/\beta}\cdot a_p^{\,1/\gamma}}$$

Design of machining processes

Process metric → Specific process metric → Specific process metric minimization

- In order to identify the optimal machining strategy to minimize each process outcome, the value of a specific process parameter (i.e., v_c, f, or a_p) where the equations' derivative is zero could be computed.

$$\frac{\partial U_C}{\partial v_c}=\frac{60}{1000}\cdot\left[\frac{\left(h_c+x_{EL}\cdot P_{stb}\right)\cdot t_3+x_{TE}}{a_p^{(1-1/\gamma)}\cdot f^{(1-1/\beta)}\cdot v_c^{(2-1/\alpha)}}\cdot\frac{1-\alpha}{\alpha}\cdot\frac{1}{A}-\frac{h_c+x_{EL}\cdot\left(P_{stb}+b+c+P_{lub}\right)+x_L\cdot q_L}{a_p\cdot f\cdot v_c^{2}}\right]=0$$

- $$v_c^{\min U_C}=\left\{\frac{A\cdot\left[h_c+x_{EL}\cdot\left(P_{stb}+b+c+P_{lub}\right)+x_L\cdot q_L\right]}{a_p^{1/\gamma}\cdot f^{1/\beta}\cdot\left[\left(h_c+x_{EL}\cdot P_{stb}\right)\cdot t_3+x_{TE}\right]}\cdot\frac{\alpha}{1-\alpha}\right\}^{\alpha}$$

- $$T_{\min U_C}=\frac{\left(h_c+x_{EL}\cdot P_{stb}\right)\cdot t_3+x_{TE}}{h_c+x_{EL}\cdot\left(P_{stb}+b+c+P_{lub}\right)+x_L\cdot q_L}\cdot\left(\frac{1-\alpha}{\alpha}\right)$$

- Obviously, the terms being independent of process parameter variations are nullified when deriving.

Design of machining processes

Process metric → Specific process metric → Specific process metric minimization → Process optimization

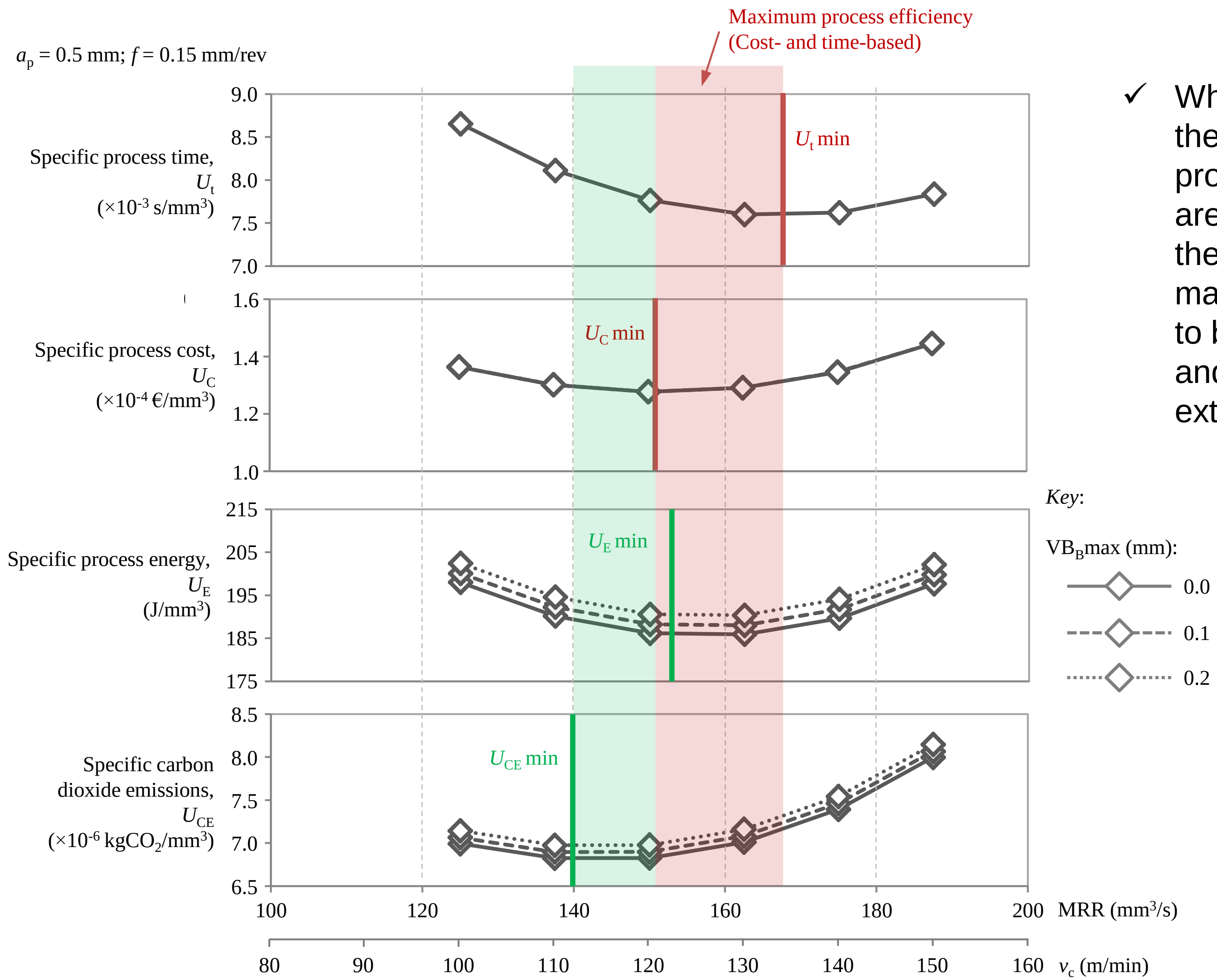
Objective: to minimize	Cutting speed	Tool life
Process time	$v_c^{\min U_t} = \left(\frac{A}{a_p^{1/\gamma} \cdot f^{1/\beta} \cdot t_3} \cdot \frac{\alpha}{1-\alpha} \right)^{\alpha}$	$T_{\min U_t} = t_3 \cdot \left(\frac{1-\alpha}{\alpha} \right)$
Process cost	$v_c^{\min U_C} = \left\{ \frac{A \cdot \left[h_c + x_{EL} \cdot (P_{\mathrm{stb}} + b + c + P_{\mathrm{lub}}) + x_L \cdot q_L \right]}{a_p^{1/\gamma} \cdot f^{1/\beta} \cdot \left[(h_c + x_{EL} \cdot P_{\mathrm{stb}}) \cdot t_3 + x_{TE} \right]} \cdot \frac{\alpha}{1-\alpha} \right\}^{\alpha}$	$T_{\min U_C} = \frac{(h_c + x_{EL} \cdot P_{\mathrm{stb}}) \cdot t_3 + x_{TE}}{h_c + x_{EL} \cdot (P_{\mathrm{stb}} + b + c + P_{\mathrm{lub}}) + x_L \cdot q_L} \cdot \left(\frac{1-\alpha}{\alpha} \right)$
Primary energy demand	$v_c^{\min U_E} = \left\{ \frac{A \cdot \left[\frac{1}{\eta} \cdot (P_{\mathrm{stb}} + b + c + P_{\mathrm{lub}}) + y_L \cdot q_L \right]}{\left(a_p^{1/\gamma} \cdot f^{1/\beta} \right) \cdot \left(\frac{1}{\eta} \cdot P_{\mathrm{stb}} \cdot t_3 + y_{TE} \right)} \cdot \left(\frac{\alpha}{1-\alpha} \right) \right\}^{\alpha}$	$T_{\min U_E} = \frac{\left(\frac{1}{\eta} \cdot P_{\mathrm{stb}} \cdot t_3 + y_{TE} \right) \cdot \left(\frac{1-\alpha}{\alpha} \right)}{\frac{1}{\eta} \cdot (P_{\mathrm{stb}} + b + c + P_{\mathrm{lub}}) + y_L \cdot q_L}$
CO_2 emissions	$v_c^{\min U_{CE}} = \left\{ \frac{A \cdot \left[\mathrm{CES} \cdot (P_{\mathrm{stb}} + b + c + P_{\mathrm{lub}}) + z_L \cdot q_L \right]}{a_p^{1/\gamma} \cdot f^{1/\beta} \cdot (\mathrm{CES} \cdot P_{\mathrm{stb}} \cdot t_3 + z_{TE})} \cdot \left(\frac{\alpha}{1-\alpha} \right) \right\}^{\alpha}$	$T_{\min U_{CE}} = \left(\frac{\mathrm{CES} \cdot P_{\mathrm{stb}} \cdot t_3 + z_{TE}}{\mathrm{CES} \cdot (P_{\mathrm{stb}} + b + c + P_{\mathrm{lub}}) + z_L \cdot q_L} \right) \cdot \left(\frac{1-\alpha}{\alpha} \right)$

Design of machining processes

- The longitudinal external turning of a Ti-6Al-4V alloy has been assumed as a case study.

- Experimental tests:
  - Graziano CNC lathe
  - Uncoated RCMT 1204 M0-SM H13A cutting inserts
  - Wet cutting: oil-in-water emulsion supplied by the flood cooling system of the machine tool
    (at a flow rate of 10 l/min)
  - (Semi-)finishing cutting conditions:
    - ✓ The depth of cut (a_p) and the feed (f) have been fixed to 0.5 mm and 0.15 mm/rev, respectively
    - ✓ The cutting speed (v_c) was changed within the range of 100 to 150 m/min.
    - ✓ The variation in MRR (from 125 to 187.5 mm^3/s) has proved to heavily affect the tool life performance.

Design of machining processes



- ✓ When the metrics for the environmental process sustainability are introduced, the high-efficiency machining range has to be reconsidered and, in some cases, extended.

Design of machining processes

- The influence of workpiece material deserves a digression.

- If the aim of the work is to derive the optimal machining strategy to minimize a specific process metric, the (constant) contributions not being dependent on the variations of process parameters could be neglected, since they do not affect the position of the minimum curve value.

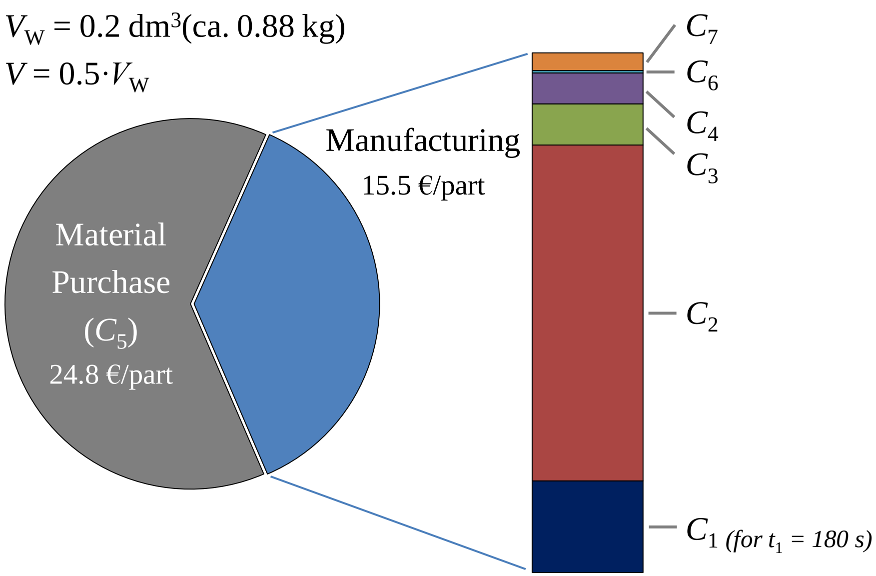
- The contributions due to workpiece material could be left out of the analysis, if the amount of needed material is only influenced by the geometry of the desired end product (assuming no difference in material losses among the different cutting conditions).

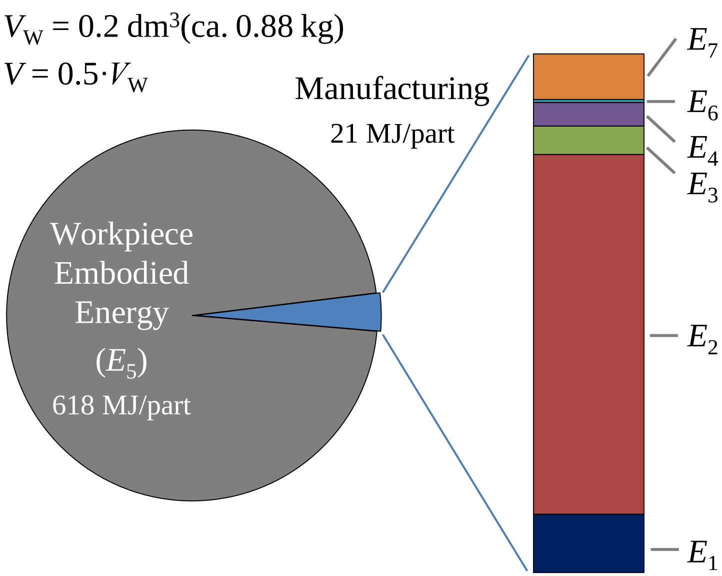
- However, this could give rise to misinterpretation of results.

- The embodied energy for the primary production of the workpiece is usually higher than the energy demand of the cutting process.

Design of machining processes

- The influence of workpiece material contribution for a generic component weighting 0.44 kg (= 0.1 dm³) and obtained from a workpiece of 0.2 dm³.
- All the energy and cost contributions have been computed in the local minimum.
- It is worth to underline that the purchase cost and the energy embedded in the workpiece (due to material extraction, refinement, and processing) might easily dominate all the other factors of influence.





References and further readings

- Michael F. Ashby
  Materials and the Environment:
  Eco-Informed Material Choice (2nd Edition), Elsevier (2013) ISBN: 978-0-12-385971-6

- David Dornfeld, Editor
  Green Manufacturing Fundamentals and Applications, Springer © 2013

- Dahmus J.B., Gutowski T.G.
  An environmental analysis of machining
  Proceedings of IMECE 2004, November 13-19, 2004, California USA

- Behrendt T., Zein A., Min S.
  Development of an energy consumption monitoring procedure for machine tools
  CIRP Annals - Manufacturing Technology 61 (2012) 43-46

- Kara S., Li W.
  Unit process energy consumption models for material removal processes
  CIRP Annals - Manufacturing Technology 60 (2011) 37-40

- Priarone P.C., Robiglio M., Settineri L.
  Re-thinking the maximum efficiency in machining when environmental stress is accounted for
  XIII AITEM Conference (2017)