EMO MILANO 2015, 5-10/10/2015
Technical workshop on "New manufacturing trends, perspectives and challenges"

"Sustainable Manufacturing: **Machine tool energy consumption**"

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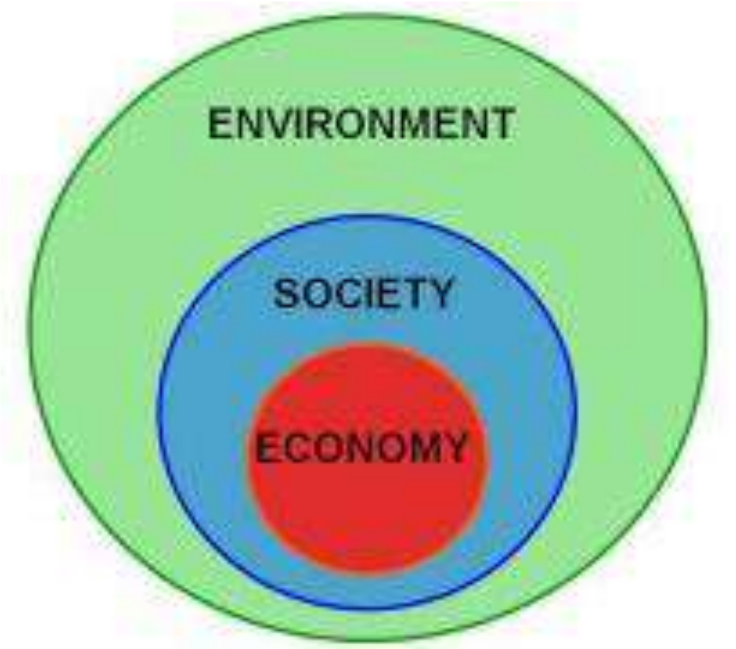
Sustainability

- Sustainable development can be defined as the capacity **to meet the needs of the present without compromising the ability of future generations to meet their own needs.**

- Sustainability has three pillars, these are Economy, Social, Environment (**Profit, People, Planet**).

- The challenge is for machine tool builders to develop a ECO-RANGE that strikes **synergy between the three sustainability pillars.**



Opportunities in Energy Efficient Manufacturing

- ✓ UK industry consumed 328 TWhr UK of electricity in 2010; assuming a cost of 11.89 pence/kWhr, this represent a UK spend of **£10 billion** on electrical energy.

- ✓ **Better material and resource efficiency leads to higher factory productivity.** When companies tackle resource efficiency they **strip bare the material inefficiencies in factories** (from a study of US manufacturing sectors and South Korean companies**).

- ✓ **In many industrial settings, abundant opportunities exist for saving 50 to 90% of the energy costs**, Rocky Mountain Institute, USA (http://www.rmi.org/rmi/).

**Hepburn H, 2012. Material efficiency in economic and climate policy. Discussion Meeting on Material Efficiency: The Royal Society, London, 30/31 Jan 12.

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Drivers for Energy Demand Reduction

- ✓ Energy generation as driven by consumption demand is a key **contributor to carbon emissions** and climate change.
- ✓ **Reducing the energy intensity of manufactured products** can help reduce manufacturing cost and product susceptibility to volatile energy prices.
- ✓ Reducing energy usage is an essential consideration in **sustainable manufacturing**.
- ✓ Mechanical machining is a dominant manufacturing route and hence represents significant energy demand in manufacturing.
- ✓ Machining optimisation has been based on economic criteria and technological considerations.

Link Between Energy and CO_2 emissions

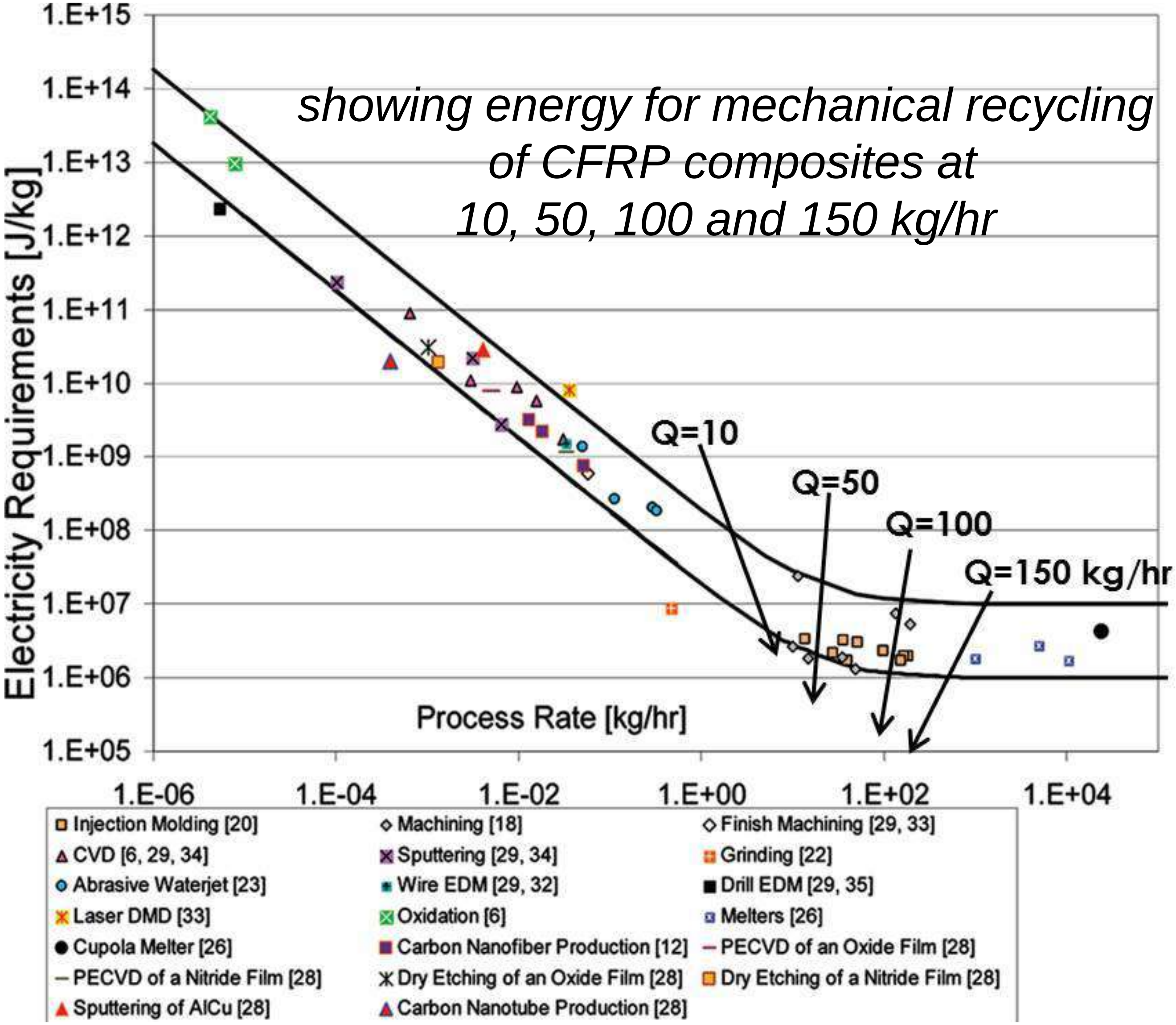
- The most common and carbon based power generation processes produce carbon dioxide emissions.
- The **power** used in manufacturing processes and machine tools **carries the environmental burden of power generation processes.**
- Mathematically, the 'Carbon Emission Signature' (CES™) can be used to determine CO_2 emissions attributed to energy generation.
- Carbon emission = Energy consumption (GJ) x CES™ ($kgCO_2$/GJ).
- CES™ is the carbon emission signature or **intensity factor as calculated for the energy grid mix.**
- An 'average carbon intensity factor for electricity fixed at 0.43 $kgCO_2$/kWh' is used for the UK.

Good News - 1

Electrical energy demand is the major factor that dominates the environment burden of machine tools.

Electricity is easier to decarbonise

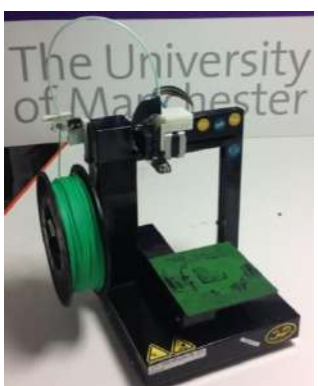
Good News 2. Hockey Stick Diagram, after Gutowski, MIT



Machine tools are very efficient manufacturing equipment

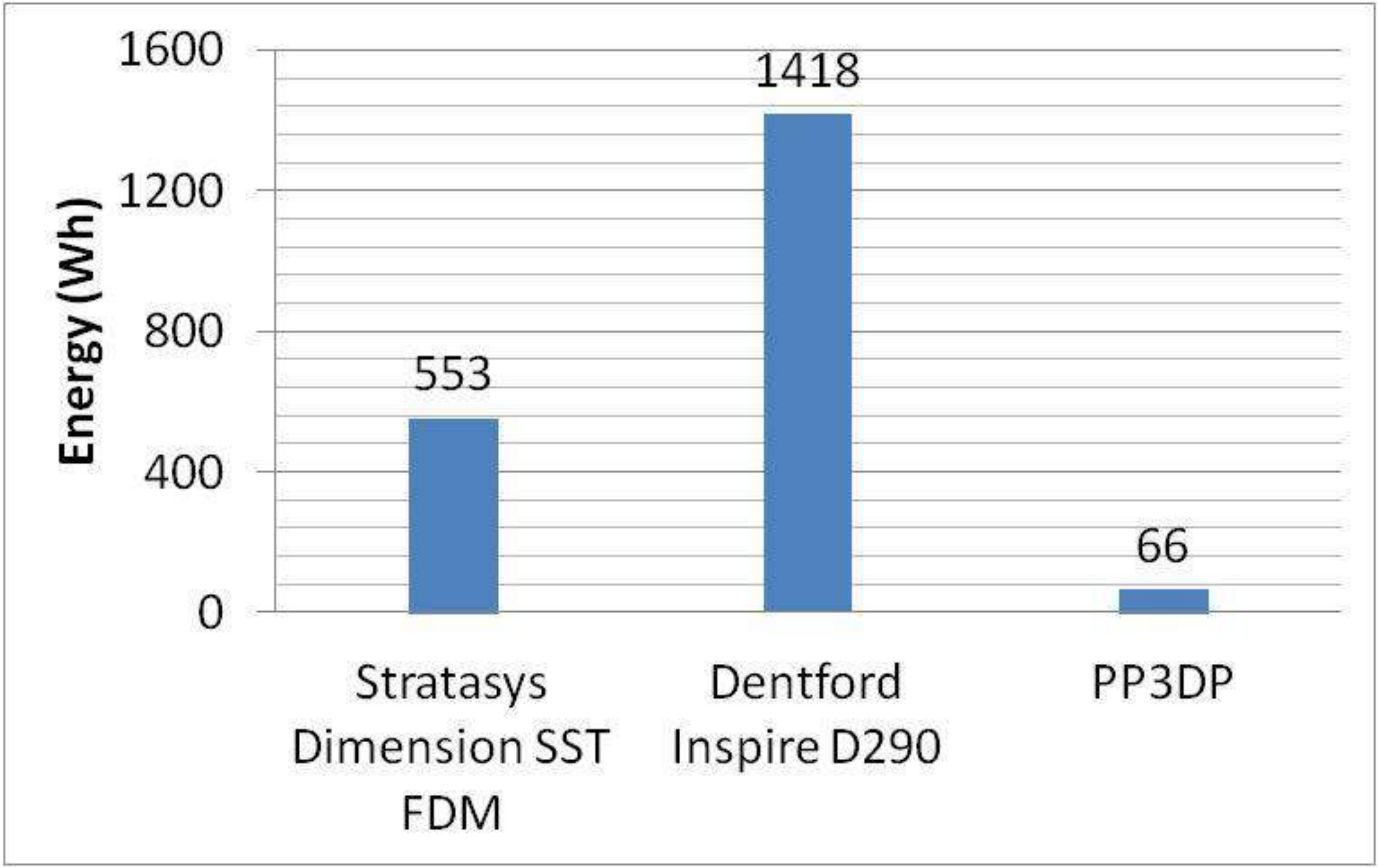
Fused Deposition Modelling Systems

– From left Dimension SST FDM, Dentford Inspire D290



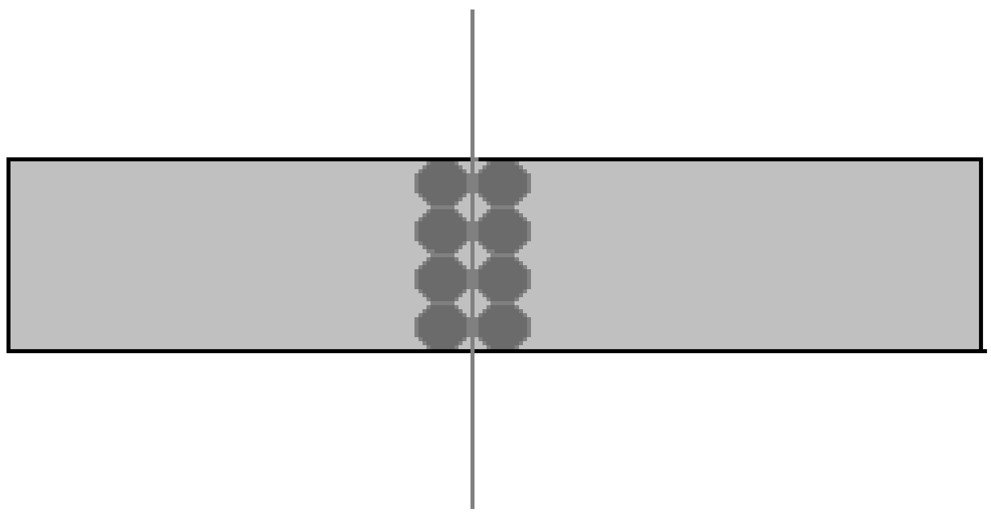
FDM machine
model
PP3DPP

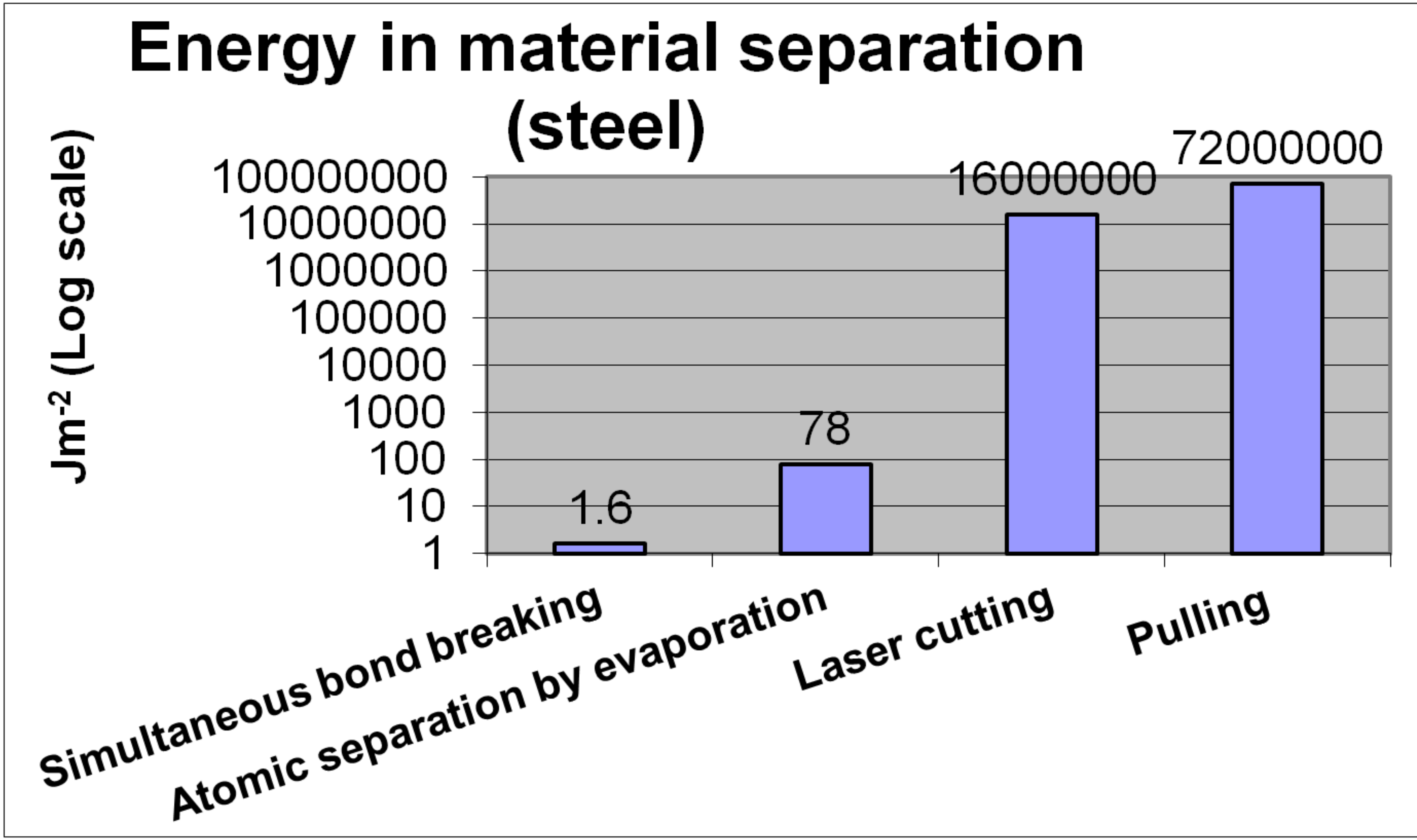
Energy demand for 3D printing a similar model on different FDM machines (first build from room temperature)



Material Removal Processes

Goal: **Clean separation of a layer of atoms**



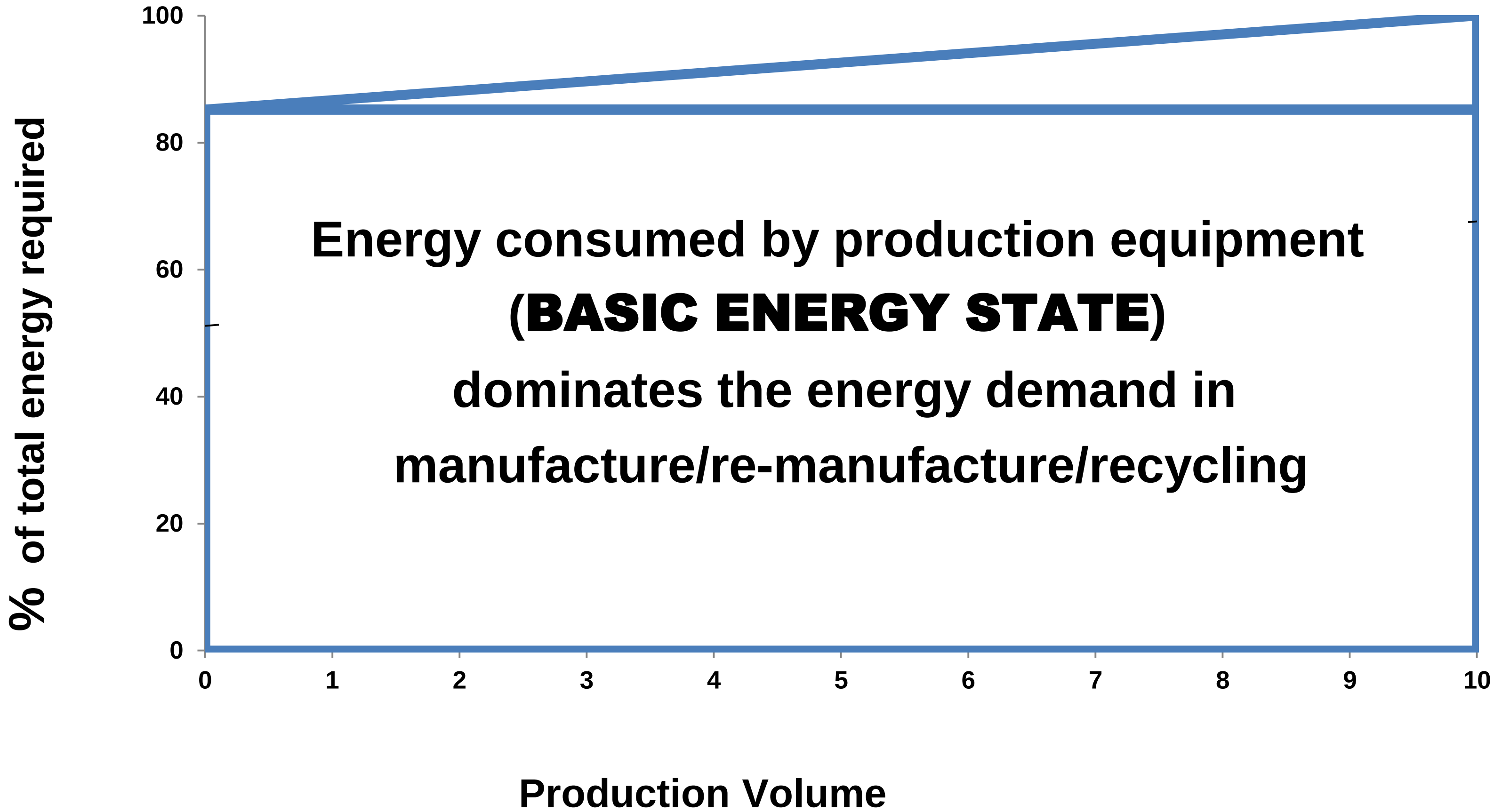


Energy in material separation (steel)
Jm-2 (Log scale)
100000000
10000000
1000000
100000
10000
1000
100
10
1
1.6
78
16000000
72000000
Simultaneous bond breaking
Atomic separation by evaporation
Laser cutting
Pulling

WORK DONE BY A FALLING BODY

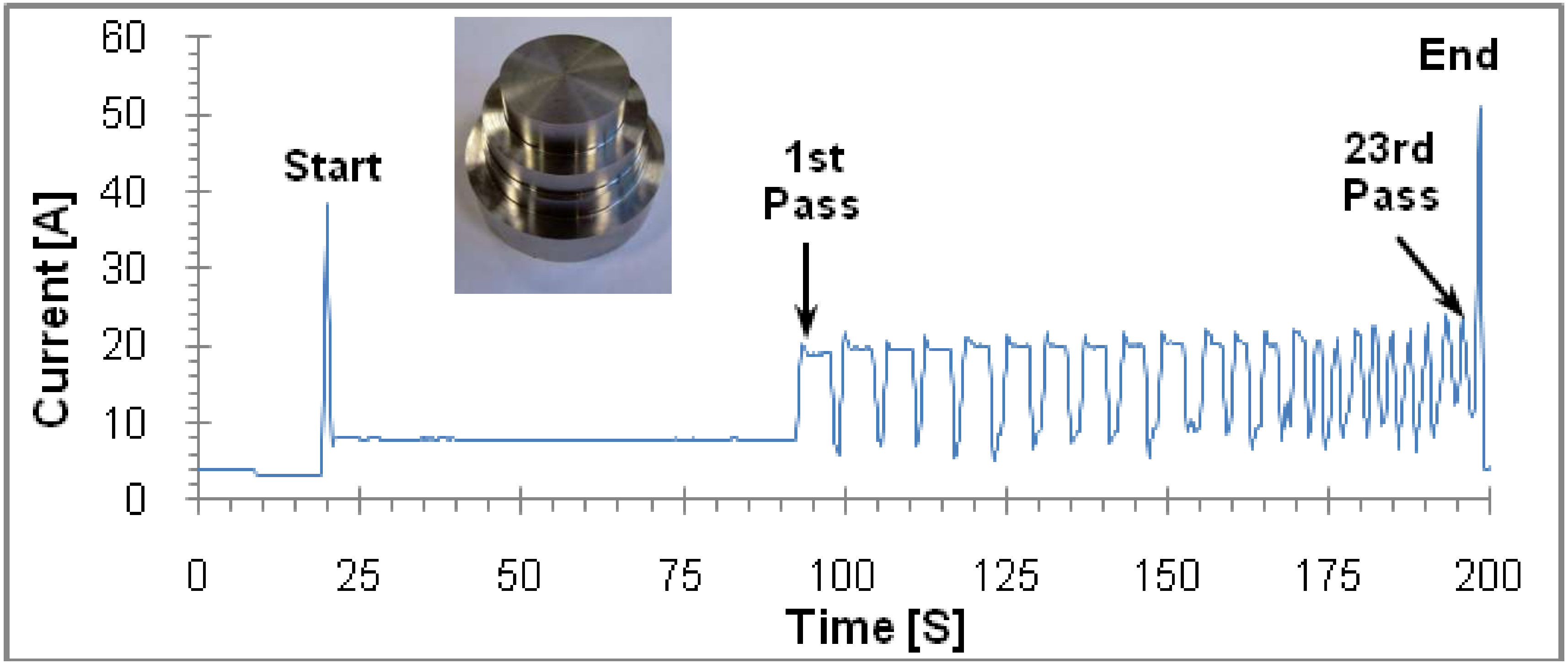
- Work done by falling body weight
- Work = Force x distance
- Average body weight of 80 kg = 800N
- If the body falls from a height of 1 cm work done = **8J**
- **If properly directed on a mm² this could severe an iron ingot.**
- ***Perhaps THERE IS SOMETHING IN KARATE***

Energy Use in a Machining Centre

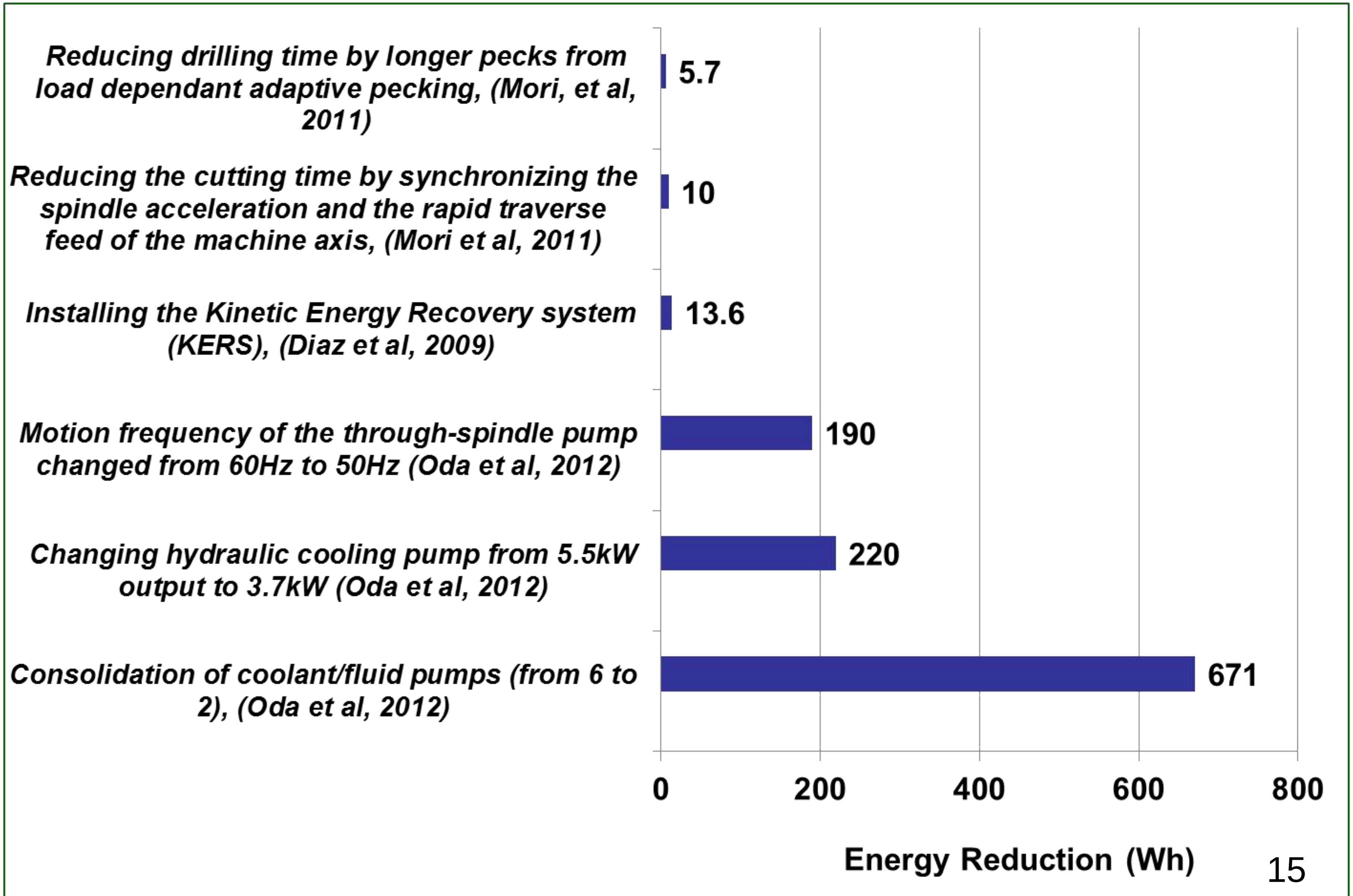


adapted **Gutowski et al., 2005., in Journal of Cleaner Production 13., pp 1–17**

Machine Tool Current Profile for Multiple Passes



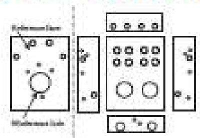
Machine Tool Energy Demand Reduction



Energy Consumption Reduction by Machining Process Improvement

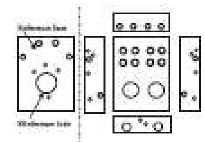
Yohei Oda, Yoshikazu Kawamura, Makoto Fujishima

1. Process Consolidation:



Drilling: 8 Machines
Finishing: 1 Machine

→



One 5-axis machine for drilling and finishing

→ 8%

2. Consolidation of Coolant Pump:

\+

From 6 pumps

1. Cyclone supply pump
2. Spindle pump
3. Shower coolant pump
4. Cooler supply pump
5. Spindle nose pump
6. Through-spindle coolant pump

Maintaining the total flow rate (420L/min) →

To 2 pumps

1. Cyclone supply (chip flush coolant and others)
2. Through-spindle coolant pump

\+

Changing the discharge pressure of the through-spindle coolant pump from 7MPa to 2MPa

→ 26%

\+

3. Optimization of Motion Frequency and Hydraulic Equipment:

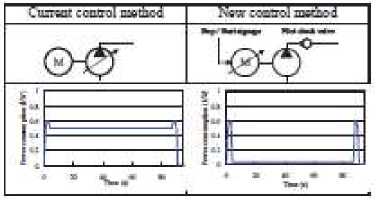
The through-spindle pump has been downsized from 5.5kW output to 3.7kW

\+

The motion frequency of the through-spindle pump has been changed from 60Hz to 50Hz

\+

Find a way to decrease the motor rotation speed of the hydraulic equipment when the hydraulic pressure is maintained.



→ 34%

\+

Decreased the motion frequency again from 50Hz to 40Hz

→ 42%

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Aim of the Research

- To develop a methodology for selecting
  – Cutting velocity (m/min)
  – Feedrate (mm/rev)
  – Depth of cut (mm)

- To ensure that the **energy used** and **apportioned to machining a component is minimised.**

Machining Optimisation Philosophy

- An objective function, is used to **calculate the desired tool life** for a given tool and cutting operation so that by using an appropriate tool life equation (optimum tool life), the corresponding optimum cutting conditions can be selected.

- The optimisation is then **done within a process window** to select a feasible combination of depth of cut a_p feed f and velocity V_c which satisfies the minimum energy criterion and process constraints.

- In single pass turning **a_p, f and V_c are independent variables,** and hence in an unconstrained situation there is no unique combination of these variables which satisfies the economic objective function.

Energy in Machining

The total energy *E* used in turning operations can be evaluated from

		Direct/Embodied	Importance
E_1	The energy consumed by the machine during setup operation	Direct	£, $, €
E_2	The energy during cutting operations	Direct	£, $, €, Quality
E_3	Energy during tool change	Direct	£, $, €
E_4	Embodied energy in the cutting tool	Embodied Energy	Footprint, Resource Synergy
E_5	Energy to produce workpiece material, cutting fluid etc.	Embodied Energy	Footprint, Resource Synergy

Energy Use in Machining

The energy *E*, required a machining process is dependant on the specific energy in cutting operations.

$$E = (P_0 + k\dot{v})t$$

Where P_o is the power consumed by an idle machine

k is the specific energy required for cutting a particular material

$\dot{v}$ is the material removal rate

t is the total machining time

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Energy Model for Turning Process

$$E = P_0 t_1 + (P_0 + k\dot{v}) t_2 + P_0 t_3 \left(\frac{t_2}{T}\right) + y_E \left(\frac{t_2}{T}\right)$$

$$E = P_0 t_1 + \frac{P_0 \pi D_{avg} l}{f V_c} + \frac{k \pi l \left(D_i^2 - D_f^2\right)}{4} + \frac{P_0 t_3 \pi D_{avg} l V_c^{\left(\frac{1}{\alpha}-1\right)} f^{\left(\frac{1}{\beta}-1\right)}}{A} + \frac{y_E \pi D_{avg} l V_c^{\left(\frac{1}{\alpha}-1\right)} f^{\left(\frac{1}{\beta}-1\right)}}{A}$$

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Optimum Tool Life For Minimum Energy

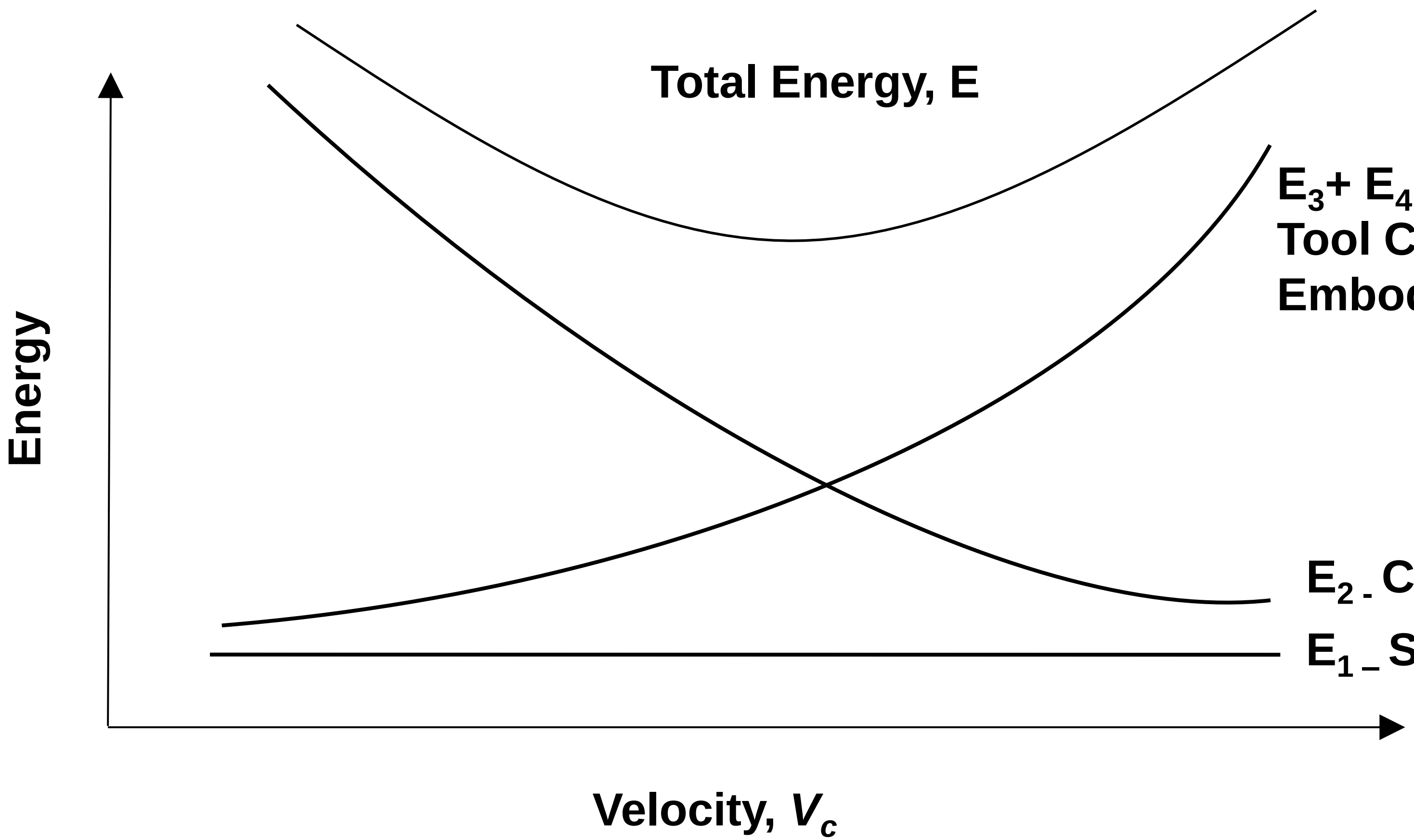
The optimum tool life for minimum energy is obtained by differentiating *E* with respect to cutting velocity and equating it to zero.

$$\frac{\partial E}{\partial V_c} = -\frac{P_0 \pi D_{avg} l}{f V_c^2} + \left(\frac{1}{\alpha} - 1\right)\frac{P_0 t_3 \pi D_{avg} l \ f^{\left(\frac{1}{\beta}-1\right)} V_c^{\left(\frac{1}{\alpha}-2\right)}}{A} + \left(\frac{1}{\alpha} - 1\right)\frac{y_E \pi D_{avg} l \ f^{\left(\frac{1}{\beta}-1\right)} V_c^{\left(\frac{1}{\alpha}-2\right)}}{A}$$

$$T_{Opt-E} = \frac{A}{f^{\left(\frac{1}{\beta}\right)} V_c^{\left(\frac{1}{\alpha}\right)}} = \left(\frac{1}{\alpha} - 1\right) \cdot \left(\frac{P_0 t_3 + y_E}{P_0}\right)$$

Machine tool and cutting tool selection are critical factors in optimising the energy footprint of machined products.

Influence of Velocity on Energy Use in Single Pass Turning



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Selecting minimum energy cutting conditions

Calculate the optimum tool life for minimum energy footprint criterion

↓

Construct a feedrate-depth of cut process window based on tool supplier and workpiece data and divide it into a grid of x by y nodes

↓

For each node check for the tool breakage constraint

↓

Evaluate the key gradients on the machine power spindle speed graph and test the power constraint

↓

Evaluate the specific energy for all the feasible nodes

↓

Evaluate energy footprint of component based on minimum specific energy and number of required passes

Case Study - Cutting Tests

- EN8 steel, (AISI1040) workpieces of an initial diameter of 130 mm and length of 300 mm were machined on a CNC MHP lathe machine.
- **CNMG120408-WF** grade 1015 inserts and PCLNL2020K12 tool holder was used.
- Process window and hence cutting conditions were derived from cutting tool supplier recommendations.
- Three different cutting speeds of **300, 400 and 500 m/min were used.**
- **Feed rate f_n of 0.15 mm/rev and depth of c**ut a_p of 1 mm were kept constant throughout machining process.
- Current was measured when running the spindle without any cutting operation and during machining process.

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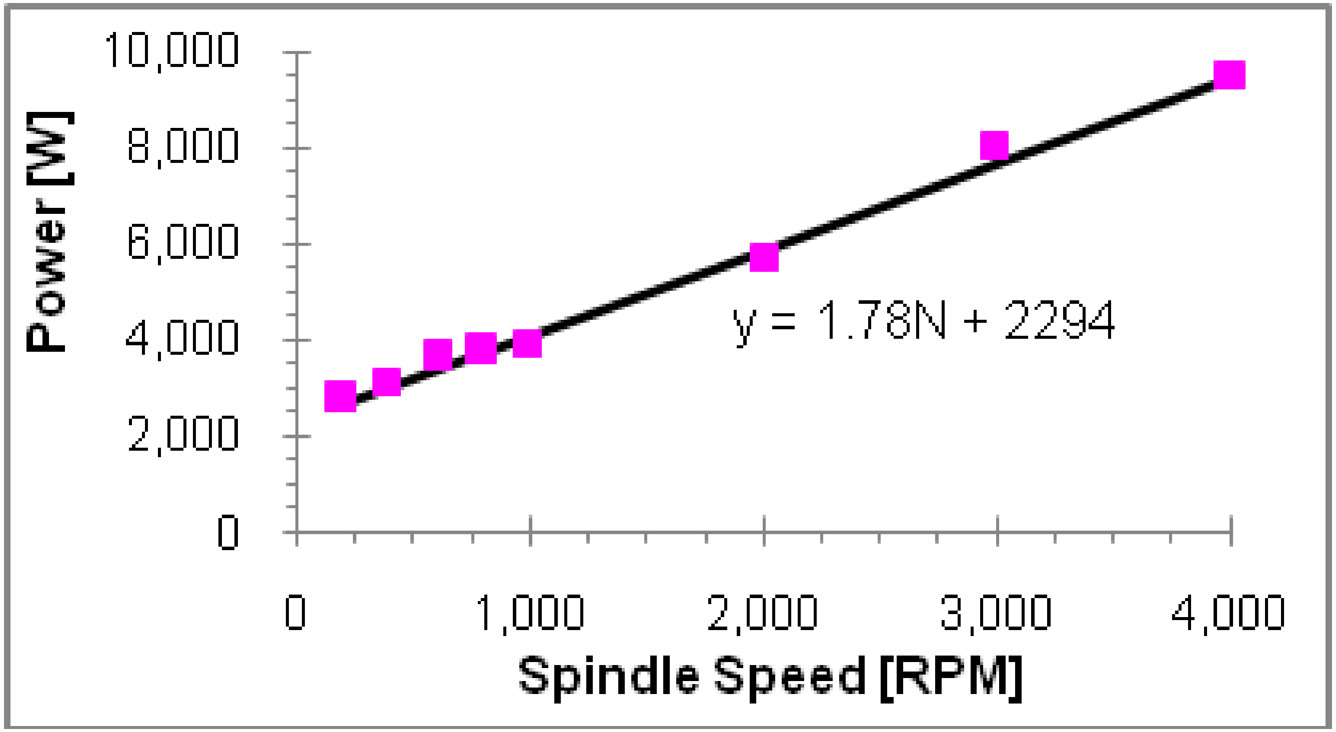
Cutting Parameters – Sandvik CNMG120408-WF

	Minimum	Maximum	Recommended
V_c [m/min]	335	555	415
f [mm/rev]	0.1	0.5	0.3
a_p [mm]	0.25	4.0	1.0

An estimate of energy footprint for carbide insert cutting tool

	Dahmus and Gutowski, 2004
Embodied tool material energy (MJ/kg)	400
Sintering and coating (MJ per cutting insert)	1 to 2 (avg 1.5)
Total energy per insert (MJ)	5.3

Machine Power When Running Spindle without Cutting



Specific energy [Ws/mm^3] in machining

a_p [mm]	**5.5**	13.1	12.9	X X	X X	X X	X X	X X X	X X X	X X X
	3.75	13.7	13.4	X X	X X	X X	X X	X X	X X	X X X
	3.50	14.3	14.0	X X	X X	X X	X X	X X	X X	X X X
	3.25	15.0	14.6	14.4	X X	X X	X X	X X	X X	X X X
	3.00	15.9	15.4	15.2	X X	X X	X X	X X	X X	X X
	2.75	X	16.4	16.1	16.0	X X	X X	X X	X X	X X
	2.50	X	17.6	17.3	17.1	X X	X X	X X	X X	X X
	2.25	X	19.0	18.7	18.5	18.3	X X	X X	X X	X X
	2.00	X	20.8	20.4	20.2	20.0	19.9	19.8	X X	X X
	1.75	X	23.0	22.6	22.4	22.2	22.0	21.9	X X	X X
	1.50	X	26.1	25.6	25.3	25.1	24.9	24.8	24.7	X X
	1.25	X	30.3	29.8	29.4	29.2	29.0	28.8	28.7	X X
	1.00	X	36.7	36.0	35.6	35.3	35.0	34.8	34.7	X X
	0.75	X	47.2	46.4	45.8	45.4	45.1	44.8	44.6	44.5
	0.50	X	X	67.0	66.2	65.6	65.2	64.8	64.5	64.3
	0.25	X	X	128	127	126	125	124	124	123
	0.00	**0.10**	**0.15**	**0.20**	**0.25**	**0.30**	**0.35**	**0.40**	**0.45**	**0.50**

feedrate [mm/rev]

X X X *–node violates the maximum available machine power constraint and sub-optimum condition does not exist*

X X *– node not feasible because the optimum cutting speed is lower than the minimum cutting speed specified by the tool supplier*

____- node made feasible by evaluating a sub-optimum cutting velocity

X *– node not feasible because the optimum cutting velocity is higher than the maximum cutting velocity set by the tool supplier*

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Minimum Cost Criterion in turning Operations

$$T_{opt-C} = \left(\frac{1}{\alpha} - 1\right)\left(\frac{x t_3 + y_C}{x}\right)$$

Where:

1/α - is the cutting velocity exponent in tool life equation,

x - is the machine cost rate in £/min,

t_3 - is tool change time in minutes and

y_c - is the tooling cost per cutting edge

after Barrow and Hinduja, UMIST, UK

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Impact of Selecting Optimum Machining Conditions

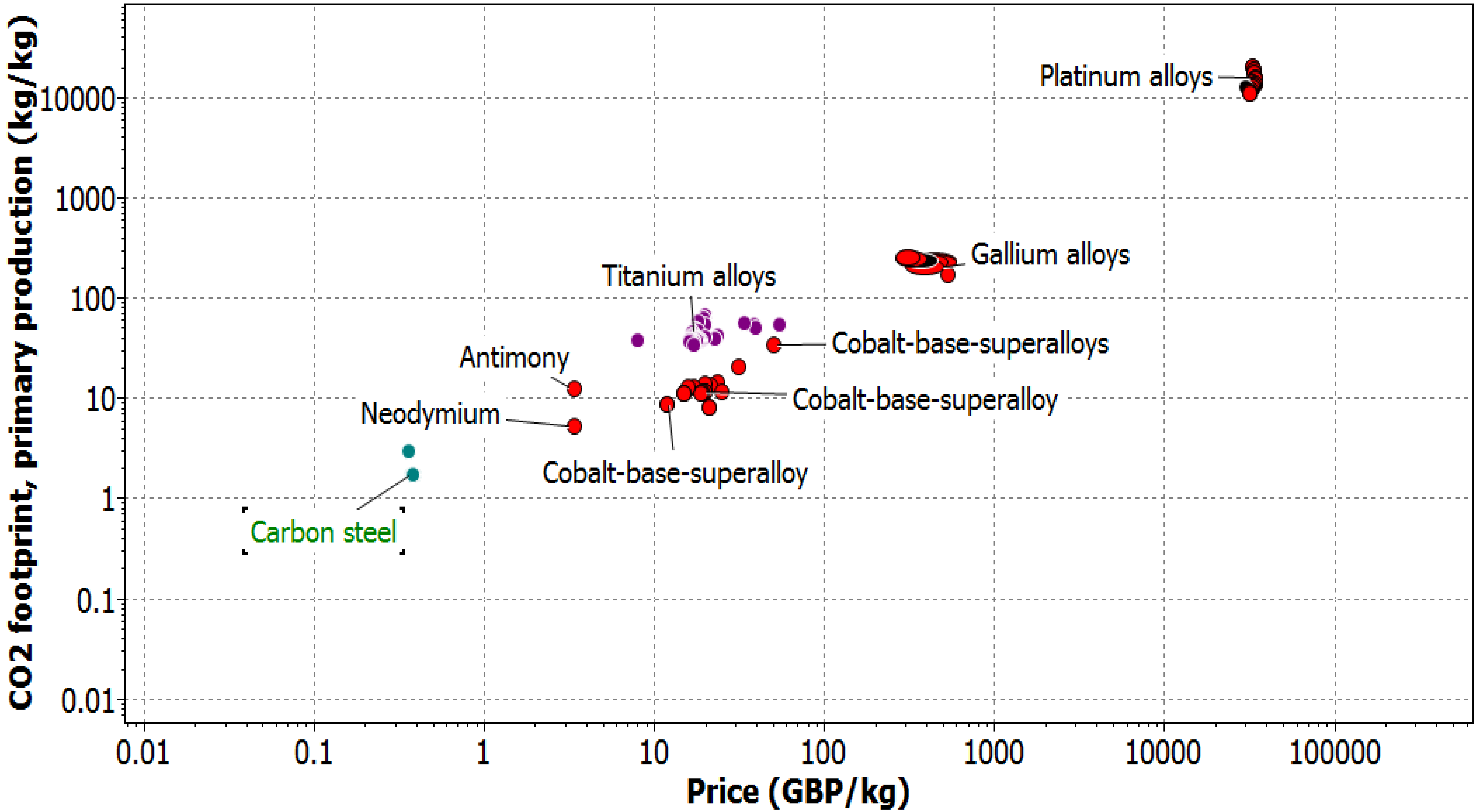
	Parameters based of tool supplier	Mid range process Window	Parameter based on minimum cost	Parameter based on minimum energy
Depth of cut (mm)	1.0	2.0	4.0	4.0
Feedrate (mm/rev)	0.3	0.3	0.15	0.15
Cutting velocity (m/min)	415	382	341	341
Number of passes	4	2	1	1
Total volume removed [mm^3]	59112	59112	59112	59112
Energy per volume removed [Ws/mm^3]	36.18	20.40	12.85	12.85
Energy footprint [kWs]	**2138.5**	**1206**	**760**	**760**
% difference from tool supplier parameters	-	**44 %**	**64 %**	**64 %**
Cost/volume $1x\ 10^{-5}$ [$£/mm^3$]	7.36	3.72	1.98	1.98
Total cost [£]	**4.35**	**2.20**	**1.17**	**1.17**

Reducing Carbon Emission

- ✓ Based on the UK CES of 0.43kgCO_2e/kWhr, the energy saving is equivalent to **a reduction from 255 to 91g of CO_2e for energy derived emissions.**

- ✓ **In Context: In the UK, the carbon footprint of a pint of TESCO milk is 700g for skimmed milk and 900g for whole milk.**

Environmental and Economic Synergies



Derived from CES software

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Main Points

- The critical parameters for optimum tool life for minimum energy footprint are:

  ✓ The resource **power of the machine when operating without cutting load**,

  ✓ The **energy footprint for tooling**,

  ✓ **Tool change duration,** and

  ✓ Cutting velocity exponent in the tool life equation - **wear resistance of the cutting tool**.

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Main Points

- ✓ If the total **energy footprint** for a product is **modelled mathematically** this can form the **basis of optimisation** of the energy footprint.
- ✓ The cutting velocity for minimum energy and consequently, machining cycle time is strongly influenced by the way in which **the energy of the cutting tool is accounted for.**
- ✓ It is **essential to have some consensus on the system boundaries** for optimising energy footprint in order not to result in conflicting outcomes.
- ✓ In general, **the more inclusive/comprehensive the energy requirements for tooling are accounted for,** the more likely the machining process has to be performed at relatively lower cutting speed to ***extract more value out of high energy tooling***.
- ✓ It should however, be noted that the optimum condition for one operation may not be the conditions to give ***optimum performance of a complete manufacturing system.***
- ✓ The minimum energy criterion can be applied to the selection of cutting conditions to ***machine an actual component*** *as in the case of the minimum cost criterion.*

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Conclusions - Energy Smart

- ✓ **Energy usage** is a major environmental burden associated with the use of materials.
- ✓ Manufacturing processes or **machine tools** are **NOT ALL CREATED EQUAL** with respect to **energy footprint and environmental burden. End users have a choice.**
- ✓ Designers and manufactures of machine tools have the greatest margin for improving energy efficiency in machining allowing users to **extract MORE FROM LESS** in utilising energy.
- ✓ Inefficient use of energy in materials and machine tools creates **COLLATERAL DAMAGE** to the quality of products manufactured in addition to increasing environmental burden.

The Future

- A **machine tool of the future would be energy smart – hibernating into low or energy neutral mode by some event driven logic.**

- **90% reduction in Basic Energy State ?** - Ten times lower power demand for preparing the machine to cut, compared to current generations.

- **Communing data** - Connected by sensors enabling exploitation of big data.

- **Resource Smart – (energy-tooling-cutting fluids).**

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Thank you