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Comparative Analysis of Conventional and Non-Conventional Manufacturing Processes

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ABSTRACT

The growing use of hard-to-machine alloys, complex geometries and stringent surface-finish requirements makes process selection an important manufacturing decision. This study compares eight conventional and non-conventional processes (CNC machining, grinding, EDM, wire EDM, ECM, ultrasonic, laser and abrasive jet machining) on material removal rate, surface roughness, tolerance, specific energy, tool wear, hard-material capability and geometric complexity. Representative handbook and literature values for hardened steel and nickel-based alloys were analysed in MATLAB using TOPSIS under three application scenarios, together with a cost-per-part break-even model. Specific energy ranged from about 4 J/mm³ (CNC machining) to 800 J/mm³ (abrasive jet machining). For high-volume productivity, CNC machining ranked first (closeness coefficient 0.801) followed by ECM (0.480). For precision machining of hard materials, grinding (0.650) and ECM (0.644) led, and for complex geometries in hard materials ECM ranked first (0.618), followed by CNC machining (0.594) and wire EDM (0.560). Across 2,000 random ±20% weight perturbations, the top-ranked process remained unchanged in 100%, 57% and 73% of cases for the three scenarios. In the illustrative cost model, wire EDM was cheaper than CNC machining below about 41 parts per batch, and ECM above about 198 parts. The study offers a systematic framework for selecting machining processes on technical, operational and economic grounds.

Keywords: Conventional Machining, Non-Conventional Machining, EDM, Wire EDM, ECM, Material Removal Rate, Specific Energy Consumption, TOPSIS, Process Selection, Cost Analysis, MATLAB

I. INTRODUCTION

Manufacturing processes that remove material to produce a part may be divided into conventional and non-conventional groups. Conventional processes such as turning, milling, drilling, shaping and grinding rely on a cutting tool or abrasive that is harder than the workpiece and that removes chips by direct mechanical contact; they are fast, economical and well understood, and they remain the backbone of metalworking [1], [2]. Non-conventional, or non-traditional, processes remove material by thermal, electrochemical, chemical or mechanical energy that does not depend on the hardness of the tool, and therefore can machine materials and shapes which are difficult or impossible to produce by conventional means [3], [4].

The need for non-conventional processes has grown because of the introduction of materials such as nickel and titanium superalloys, hardened tool steels, ceramics and composites that wear out conventional tools rapidly [5], and because of the demand for micro-features, deep slots, sharp internal corners and delicate parts for aerospace, medical, die-and-mould and electronic applications. However, non-conventional processes are generally slower, consume more energy per unit volume removed and have higher capital and operating costs, so that they are not a universal replacement for conventional machining. A rational comparison is thus necessary to determine which process should be used for a given job.

The comparison is complicated by the fact that the processes differ on many criteria which are often in conflict, so that the process with the highest removal rate may produce the roughest surface or the highest energy consumption. The purpose of the present paper is therefore (i) to compare conventional and non-conventional processes on seven technical criteria, (ii) to rank the processes for three typical application scenarios using the multi-criteria decision method TOPSIS, (iii) to compare the cost per part as a function of batch size, and (iv) to provide guidelines for process selection. All calculations were performed in MATLAB. The paper is organised as follows: Section II briefly

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reviews the processes, Section III describes the methodology, Section IV gives the results and discussion, and Sections V and VI present the limitations and conclusions.

II. OVERVIEW OF THE PROCESSES

A. Conventional processes

In turning and milling, a single-point or multi-point cutting tool removes material in the form of chips by shear, and the removal rate is the product of the cutting speed, feed and depth of cut. Grinding uses many small abrasive grains as cutting edges and is employed for hard materials and for fine finishes and accuracy. Conventional processes offer high removal rates, good surface quality, closed-loop CNC control and low cost per unit volume for most metals, but the tool wear rises sharply for hard or heat-resistant alloys such as Inconel and titanium because of the high cutting forces and temperatures [5].

B. Non-conventional processes

Electrical discharge machining (EDM) removes material by the melting and vaporisation of tiny volumes by repeated sparks between an electrode and the work in a dielectric fluid; it requires an electrically conductive work material but not a hard tool [6]. Wire EDM (WEDM) uses a travelling thin wire as the electrode to cut profiles through hard conductive material. Electrochemical machining (ECM) removes material by controlled anodic dissolution, with no tool wear and no thermal damage, and can machine complex cavities in hard alloys [3], [7], [8]. Ultrasonic machining (USM) uses abrasive slurry driven by a vibrating tool and is suitable for hard and brittle materials such as glass and ceramics. Laser beam machining (LBM) uses the thermal energy of a focused beam, and abrasive-jet machining (AJM) uses a high-velocity stream of fine abrasive particles for deburring, cleaning and cutting of thin, brittle sheets [4]. Fig. 1 summarises the classification.

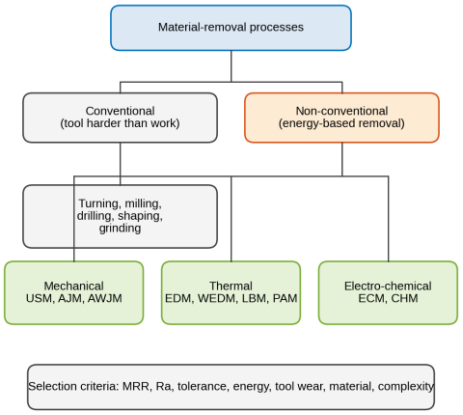


Fig. 1: Classification of conventional and non-conventional material-removal processes

C. Working principles and workpiece requirements

Table 1 contrasts the main characteristics of the processes. In conventional machining the tool must be harder and tougher than the work, and the energy is mechanical. In non-conventional processes the removal mechanism is electrical, chemical or mechanical in a way that does not depend on tool hardness, so the tool can be softer than the work or can be a non-contact medium such as a spark, an electrolyte, a laser beam or an abrasive jet. This explains their ability to cut hardened alloys, but it also imposes workpiece restrictions: EDM, WEDM and ECM need an electrically conductive material, USM and AJM work best on brittle materials, and LBM is limited by the reflectivity and thermal conductivity of the work. Residual-stress and heat-affected-zone effects also differ: ECM leaves a stress-free surface, whereas EDM and LBM leave a recast layer that may need removal in fatigue-critical parts.

Table 1: Working principles and workpiece requirements

Process	Energy / medium	Workpiece requirement
CNC machining, grinding	Mechanical; hard tool or abrasive	Machinable metal; hardness limits tool life
EDM, WEDM	Thermal; spark in dielectric	Electrically conductive
ECM	Electrochemical; electrolyte	Electrically conductive
USM	Mechanical; abrasive slurry, vibration	Preferably hard and brittle
LBM	Thermal; focused laser beam	Absorbs laser; thin sections
AJM	Mechanical; abrasive jet	Brittle or thin materials

III. MATERIALS AND METHODOLOGY

A. Workflow

The method is shown in Fig. 2. Eight processes (CNC machining representing turning and milling,

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grinding, EDM, WEDM, ECM, USM, LBM and AJM) are selected, and their indicative performance data are compiled. The decision matrix is normalised, three sets of criterion weights are assigned for three application scenarios, and the processes are ranked by TOPSIS. The stability of the ranking is tested by random perturbation of the weights, and a cost-per-part model is used to find break-even batch sizes.

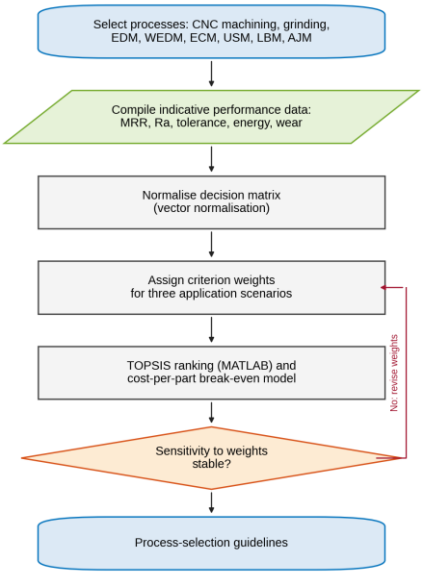


Fig. 2: Flow chart of the comparative analysis and process-selection procedure

B. Criteria and indicative data

Seven criteria were selected: material removal rate (MRR), surface roughness R_a, achievable tolerance, specific energy, tool wear, capability for hard materials and capability for geometric complexity. The first four are quantitative; the last three are rated on a scale of 1–5, with 5 being the highest capability or, for tool wear, the highest wear. Data for machining a hardened steel or nickel-based alloy of about 40 HRC are given in Table 2. They are typical values within the ranges quoted in standard references [1]–[5], [10] and rounded for use in a comparative study; they are not measurements and actual values depend on the material, machine, tool and parameters. For this reason the ranking should be seen as a method of reasoning rather than a final selection.

Table 2: Indicative performance data for hard-material machining

Process	MRR (mm³/min)	R_a (µm)	Tol. (±µm)	SE (J/mm³)	Wear	Hard	Cmplx
CNC machining	8000	1.6	20	4	4	2	4
Grinding	600	0.4	5	40	3	4	2
EDM	120	2.5	15	250	3	5	5
WEDM	90	1.6	8	400	2	5	4
ECM	3000	0.8	25	100	1	5	4
USM	20	0.8	15	600	3	4	4
LBM	40	3.2	30	500	1	4	3
AJM	5	0.8	50	800	2	3	3

C. Process relations

The MRR in turning is the product of the cutting speed v, the feed f and the depth of cut d:

$$MRR_{turn} = v \cdot f \cdot d \quad (1)$$

For example, machining a hard alloy at v = 20 m/min, f = 0.2 mm/rev and d = 2 mm gives 8000 mm³/min, the value used in Table 2. In ECM the removal rate follows Faraday's law:

$$MRR_{ECM} = \eta_c I A / (z F \rho) \quad (2)$$

where η_c is the current efficiency, I the current, A the atomic mass, z the valency, F Faraday's constant (96,485 C/mol) and ρ the density. For steel (A = 55.85 g/mol, z = 2, ρ = 7.85 g/cm³) at I = 1000 A and η_c = 0.9, the removal rate is 33.2 mm³/s, i.e. about 1990 mm³/min, which is of the same order as the 3000 mm³/min given in Table 2 for a higher current. The energy per spark in EDM is $E_s = V_g I t_{on}$, and the removal rate increases with the spark energy and frequency but at the expense of surface roughness. The specific energy of any process is the power consumed in cutting divided by the removal rate:

$$u = P / MRR \quad (3)$$

For CNC machining at 8000 mm³/min and 4 J/mm³ the cutting power is 533 W, whereas for EDM at 120 mm³/min and 250 J/mm³ it is 500 W; the same power thus removes a volume nearly 70 times smaller by EDM.

D. TOPSIS ranking

TOPSIS ranks the alternatives according to their closeness to the ideal solution [9]. The decision matrix x_{ij} is normalised by vector normalisation, weighted, and the distances to the ideal and anti-ideal solutions computed:

$$r_{ij} = x_{ij} / \sqrt{(\Sigma_i x_{ij}^2)}, \quad v_{ij} = w_j r_{ij} \quad (4)$$

$$C_i = d_i^- / (d_i^+ + d_i^-) \quad (5)$$

where d_i^+ and d_i^- are the Euclidean distances of alternative i from the ideal and the anti-ideal points and C_i is the closeness coefficient (0–1); a higher value is better. MRR, hard-material capability and complexity are treated as benefit criteria, and R_a, tolerance, specific energy and tool wear as cost

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criteria. Three scenarios were defined by the weights of Table 3: S1, high-volume productivity; S2, precision machining of hard material; and S3, complex shapes in hard material.

Table 3: Criterion weights for the three scenarios

Criterion	S1	S2	S3
MRR	0.30	0.10	0.10
R_a	0.10	0.20	0.10
Tolerance	0.10	0.20	0.15
Specific energy	0.15	0.05	0.05
Tool wear	0.15	0.10	0.10
Hard-material capability	0.10	0.25	0.25
Complexity	0.10	0.10	0.25

E. Cost-per-part model

The cost per part for a batch of n parts is

$$C(n) = S / n + c_m t_m + c_t \quad (6)$$

where S is the batch set-up and special tooling cost, c_m the machine-hour rate, t_m the machining time per part and c_t the consumable and tooling cost per part. Illustrative values for a hard-alloy part are given in Table 4 for CNC machining, WEDM and ECM; the ECM figure includes a dedicated tool and fixture that must be designed and made for the part. The values are assumed, in Indian rupees (INR), and are intended to show the structure of the trade-off rather than any particular shop.

Table 4: Illustrative cost-model inputs (INR)

Item	CNC	WEDM	ECM
Set-up/tooling S (per batch)	4000	2500	122,500
Machine rate c_m (INR/h)	900	1000	1500
Time t_m (min)	22	40	6
Consumables c_t (per part)	450	150	30

F. MATLAB implementation

The decision matrix was held in a MATLAB array, with vector normalisation by the norm function, ideal and anti-ideal points found with max and min, and the closeness coefficient calculated using vectorised operations. The robustness of the ranking was tested by Monte Carlo simulation: in each of 2000 trials every weight was multiplied by a random factor between 0.8 and 1.2 and the weights renormalised, and the fraction of trials in which the first-ranked process remained first was recorded. The cost model was evaluated for n = 1 to 500 and plotted on logarithmic axes, and the break-even batch sizes were found by equating the costs per part.

IV. RESULTS AND DISCUSSION

A. Removal rate and surface roughness

Fig. 3 plots the typical R_a against the MRR for the eight processes. CNC machining has by far the highest removal rate, 8000 mm³/min, followed by ECM at 3000 mm³/min and grinding at 600 mm³/min. EDM, WEDM, USM, LBM and AJM are two to three orders of magnitude lower, with AJM at only 5 mm³/min. In surface quality, grinding is the best at 0.4 µm R_a, followed by ECM, USM and AJM at 0.8 µm; the thermal processes EDM and LBM give the roughest surfaces of 2.5 and 3.2 µm because of the recast layer and the craters formed by the melting and vaporisation. ECM is the only process that combines a high removal rate with a good surface and no thermal damage, which is the reason why its ranking is high in the scenarios that follow.

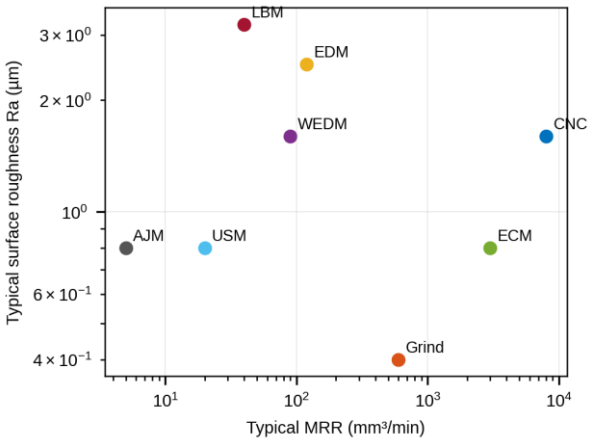


Fig. 3: Typical surface roughness versus material removal rate for eight processes

B. Specific energy

The specific energy (Fig. 4) varies by a factor of 200: 4 J/mm³ for CNC machining, 40 J/mm³ for grinding, 100 J/mm³ for ECM, 250 and 400 J/mm³ for EDM and WEDM, 500 J/mm³ for LBM, 600 J/mm³ for USM and 800 J/mm³ for AJM. The reasons are the mechanisms of removal: in cutting, energy is used for shear of a relatively large chip, while in grinding the many small chips and the rubbing and ploughing by the abrasive raise the specific energy by about an order of magnitude. In EDM, LBM and USM the volume removed by each pulse or impact is minuscule compared with the energy supplied and the heat transferred to the work and the dielectric. The non-conventional processes are therefore justified by their capability, not by

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their energy efficiency, and the difference should be considered in assessing the environmental impact.

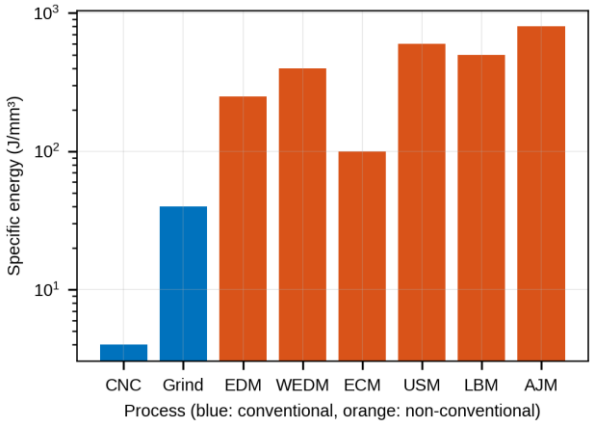


Fig. 4: Specific energy of conventional (blue) and non-conventional (orange) processes

C. Normalised performance profile

The normalised scores of Fig. 5 show the strengths of each process at a glance. CNC machining is best in MRR and energy but poor in hard-material capability and tool wear. Grinding is the best in surface roughness and tolerance. EDM and WEDM are the highest in hard-material capability and, with EDM, in complexity. ECM has the most balanced profile, with a high MRR, no tool wear, a good surface and full capability for hard materials, but it has a relatively wide tolerance because of the stray current and the difficulty of controlling the gap. LBM and AJM are less competitive in the present set of criteria, though they have unique advantages in micro-machining, thin sections and heat-sensitive or brittle materials that are not captured in the criteria.

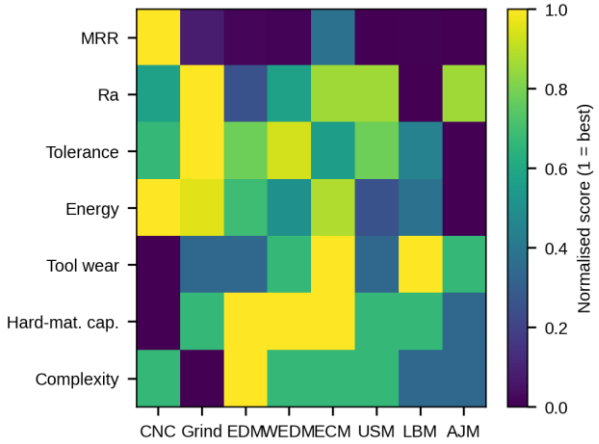


Fig. 5: Normalised performance profile of the eight processes (1 = best)

D. TOPSIS ranking

The closeness coefficients are listed in Table 5 and plotted in Fig. 6. In scenario S1 (productivity), CNC machining is clearly the best at 0.801, followed by ECM at 0.480 and grinding at 0.332; the thermal and abrasive non-conventional processes score 0.18–0.26 because of their low removal rates. In scenario S2 (precision, hard material) the ranking changes to grinding (0.650), ECM (0.644), CNC machining (0.594), WEDM (0.590) and USM (0.579), and the spread between the leaders is small. In scenario S3 (complex shapes in hard material) ECM (0.618) ranks first, followed by CNC machining (0.594), WEDM (0.560) and EDM (0.537).

Table 5: TOPSIS closeness coefficients and ranking

Process	S1	S2	S3
CNC machining	0.801 (1)	0.594 (3)	0.594 (2)
Grinding	0.332 (3)	0.650 (1)	0.515 (5)
EDM	0.252 (5)	0.491 (6)	0.537 (4)
WEDM	0.259 (4)	0.590 (4)	0.560 (3)
ECM	0.480 (2)	0.644 (2)	0.618 (1)
USM	0.217 (6)	0.579 (5)	0.508 (6)
LBM	0.214 (7)	0.333 (8)	0.368 (7)
AJM	0.177 (8)	0.382 (7)	0.298 (8)

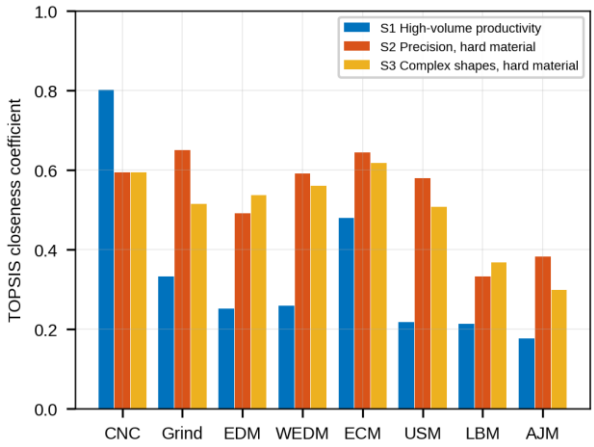


Fig. 6: TOPSIS closeness coefficient for the three application scenarios

The Monte Carlo test shows that the ranking is robust in S1, where CNC machining remained first in all 2000 trials, but is less so in S2 and S3: grinding stayed first in 57.3 % of the perturbed cases in S2 (with ECM or CNC machining taking the lead in the remainder) and ECM in 72.8 % of the cases in S3. The differences between the leading processes in S2 and S3 are small, so that other considerations such as the available equipment, the required lot size, the part material and the cost should decide between them; TOPSIS in these cases is best used to short-list two or three candidate processes.

To illustrate the calculation, consider the MRR column of Table 2. The Euclidean norm of the eight

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values is about 8.6 × 10^3 mm³/min, so the normalised MRR of CNC machining is 8000/8560 = 0.93 and that of ECM is 3000/8560 = 0.35, whereas that of EDM is only 0.014. After multiplication by the S1 weight of 0.30 the weighted values are 0.28, 0.11 and 0.004 respectively. The same procedure applied to all criteria gives the ideal and anti-ideal points, and the closeness coefficient of Eq. (5) follows from the distances to them. The large normalised value of CNC machining in the dominant MRR criterion explains its high S1 coefficient, while the 0.30 weight makes ECM, with its high removal rate, the only non-conventional process that exceeds 0.4.

E. Cost per part and break-even batch size

The cost per part from Eq. (6) is plotted against batch size in Fig. 7 and given in Table 6. For single parts, CNC machining costs INR 4780, WEDM costs INR 3317 and ECM INR 122,680 because of the cost of the tool and fixture; at a batch of ten the costs are INR 1180, 1067 and 12,430. WEDM has the lowest set-up cost and is cheaper than CNC machining for batches up to about 41 parts (the two costs are almost equal, INR 880 and 879, at 40 parts), but above that the shorter machining time and lower rate of CNC machining make it cheaper, reaching INR 788 against INR 822 at 500 parts. ECM becomes the cheapest process at about 198 parts (INR 792 at 200 parts) and at 500 parts costs INR 425 per part, 46 % less than CNC machining, because its machining time is short and the tooling cost is spread over many parts.

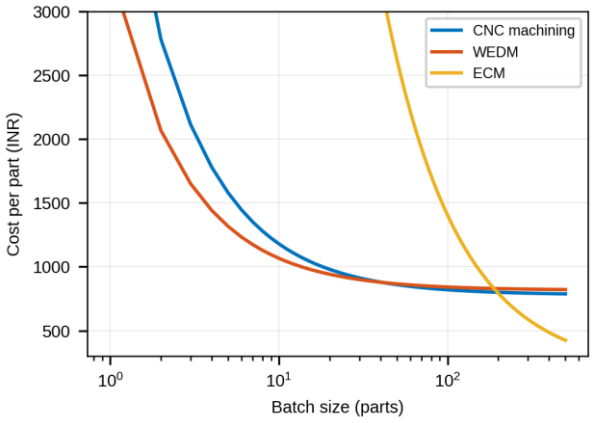


Fig. 7: Cost per part versus batch size for CNC machining, WEDM and ECM

Table 6: Cost per part (INR) for different batch sizes

Batch size	CNC	WEDM	ECM
1	4780	3317	122,680
10	1180	1067	12,430
40	880	879	3242
100	820	842	1405
200	800	829	792
500	788	822	425

The model shows the general rule of process economics: processes with low set-up cost and long machining time suit prototypes and small lots; processes with high tooling cost and short machining time suit large production runs. This is in addition to the technical capability: if the part cannot be made at all with the conventional process, for example a deep narrow slot in a hardened alloy, the cost comparison does not apply.

F. Energy and time to remove a given volume

To make the specific-energy and MRR differences concrete, Fig. 8 and Table 7 give the cutting energy and the pure machining time needed to remove 100 cm³ (10^5 mm³) of the hard alloy, calculated as u × V and V/MRR. CNC machining needs 0.11 kWh and 12.5 min, whereas ECM needs 2.8 kWh and 33 min, grinding 1.1 kWh and 2.8 h, EDM 6.9 kWh and 13.9 h, and WEDM 11.1 kWh and 18.5 h. The slow processes, USM, LBM and AJM, would need 83, 42 and 333 hours respectively for the same volume. These figures are the reason why non-conventional processes are used to remove small volumes of material, usually to cut a profile or to finish a feature, after most of the material has been removed by conventional machining. The values are cutting energies only, and exclude the auxiliary energy for pumps, dielectric filtration, power supplies and lasers, which is often as large as the cutting energy in the non-conventional processes.

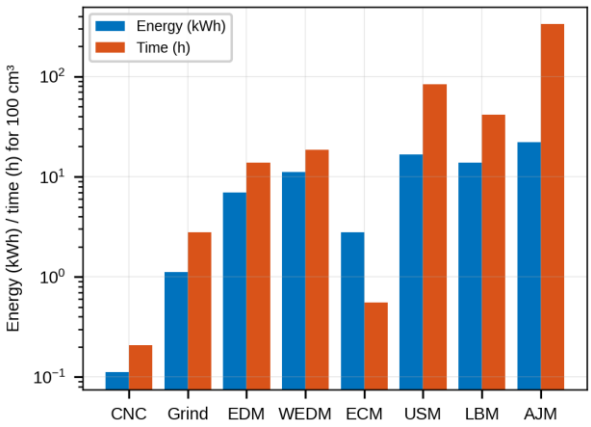


Fig. 8: Cutting energy and machining time to remove 100 cm³ of hard alloy (logarithmic scale)

Table 7: Energy and time to remove 100 cm³ of hard alloy

Process	Energy (kWh)	Time (h)
CNC machining	0.11	0.21
Grinding	1.11	2.8

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EDM	6.94	13.9
WEDM	11.1	18.5
ECM	2.78	0.56
USM	16.7	83
LBM	13.9	42
AJM	22.2	333

G. Process-selection guidelines

The results are summarised as the selection guide of Table 8. In general, conventional machining should be the first choice for any material that it can cut economically, because of its speed, low specific energy and low cost; grinding is added when a fine surface or tight tolerance on hard material is required. Non-conventional processes should be chosen when the material is too hard for cutting tools, when the geometry cannot be reached by a tool (micro-holes, deep slots, sharp internal corners, three-dimensional cavities), when the part is fragile or heat sensitive and cutting forces must be avoided, or when burr-free and stress-free surfaces are required.

Table 8: Process-selection guide

Requirement	Preferred process
High volume, machinable metals	CNC turning / milling
Fine finish and tight tolerance	Grinding; WEDM for conductive hard parts
Hard conductive material, complex profile	WEDM, EDM
Hard alloy, large batch, complex cavity	ECM
Hard, brittle non-conductors (glass, ceramics)	USM, AJM, LBM
Thin, heat-sensitive or micro features	LBM, AJM, micro-EDM

H. Illustrative application cases

The ranking can be related to familiar industrial examples. Turbine blade root slots and fir-tree profiles in nickel alloys are typically produced by WEDM, which gives the fine profile accuracy needed without cutting forces, with ECM used for the airfoil surfaces and cooling features of blade families produced in large numbers. Die and mould cavities in hardened tool steel are made by die-sinking EDM, since conventional milling of hardened steel would require expensive tooling, and are then polished. Fuel-injector nozzles and cooling holes of very small diameter are drilled by micro-EDM or lasers. Glass and ceramic parts are drilled and shaped by ultrasonic machining or abrasive jets, and medical stents and thin foils are cut with lasers because of their small, heat-sensitive sections. In all of these cases the preceding bulk of the material is removed by conventional machining and the non-conventional process is used only for the features that cannot be made otherwise.

I. Hybrid and emerging processes

The weaknesses of the individual processes have led to hybrid processes that combine two mechanisms, such as electrochemical grinding, ultrasonic-assisted turning and milling, EDM with ultrasonic vibration, and laser-assisted machining, which can raise the removal rate of non-conventional processes or reduce the tool wear and forces in conventional machining of hard materials. Additive manufacturing followed by finish machining is another route to complex shapes, one in which non-conventional processes are used for the final accurate features. These developments are expected to blur the distinction between the two groups and add new alternatives to the decision framework of this paper.

V. LIMITATIONS AND FUTURE WORK

The analysis is based on indicative data and illustrative cost inputs, not on measurements, and the numerical values and rankings should be reproduced with data for the actual material, machine and tooling before being used in a real selection. The scoring of tool wear, hard-material capability and complexity is subjective, the TOPSIS weights were chosen for illustrative scenarios, and criteria such as capital cost, environmental effects, operator skill, flexibility and availability were not included. Future work includes experimental measurement of MRR, roughness and energy on a common test material, extension of the cost model to capital depreciation and energy cost, comparison with other multi-criteria methods such as AHP and VIKOR to check the consistency of the rankings, and the inclusion of hybrid and additive processes.

VI. CONCLUSION

Eight conventional and non-conventional processes were compared using indicative data, TOPSIS and a cost model. CNC machining has the highest removal rate and lowest specific energy (4 J/mm³, compared with up to 800 J/mm³ for the non-conventional processes), and is first-ranked for productivity (closeness 0.801). For precision work on hard materials, grinding (0.650) and ECM (0.644) were the closest competitors, and for complex shapes in hard materials ECM ranked first

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(0.618), followed by CNC machining (0.594) and WEDM (0.560). The ranking was fully stable under weight perturbation in the productivity scenario and moderately stable (57 % and 73 %) in the others. In the illustrative cost model WEDM was cheapest for batches below about 41 parts, CNC machining between 41 and 198 parts and ECM above 198 parts. Non-conventional processes are therefore best seen as complements to conventional machining, to be used when the material, geometry or surface requirements exceed the capability of cutting tools.

Table 9: Nomenclature

Symbol	Meaning	Unit
MRR	Material removal rate	mm^3/min
R_a	Arithmetic mean surface roughness	µm
u, SE	Specific energy	J/mm^3
v, f, d	Cutting speed; feed; depth of cut	m/min, mm/rev, mm
η_c, I, z, F	Current efficiency; current; valency; Faraday constant	–, A, –, C/mol
C_i	TOPSIS closeness coefficient	–
w_j	Criterion weight	–
S, c_m, t_m, c_t	Set-up cost; machine rate; time; consumables	INR, INR/h, min, INR
n	Batch size	parts

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