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Eco-Design Approaches in Modern Machine Tool Construction

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Abstract

In the contemporary landscape of manufacturing, sustainability is no longer optional; it is imperative. Within this context, machine tool construction presents a unique set of challenges and opportunities: these heavy, energy-intensive pieces of capital equipment operate across long lifecycles, consume substantial embodied energy and materials, and eventually require disposal or remanufacture. This study explores eco-design approaches tailored specifically to modern machine tools, covering the full lifecycle from material sourcing and structure through operational efficiency, modularity, and remanufacturing, to end-of-life. Key strategies include lightweight and hybrid structural materials, modular and reconfigurable design enabling upgrades rather than replacement, energy-efficient drives and controls, digital monitoring for predictive maintenance, and lifecycle assessment (LCA) frameworks to guide choices. The review draws on recent literature in machine tool energy-consumption modelling, remanufacturing of conventional machines into CNC tools, modular "green" machine tool concepts, and eco-mechatronics design philosophy. It highlights how manufacturers of machine tools can integrate sustainability criteria, including resource efficiency, recyclability, energy use, and circular economy principles, into their design, manufacturing, and business models. The study also discusses barriers to adoption (cost, standards, market acceptance) and proposes a roadmap for future research and industrial implementation. Ultimately, the aim is to provide both an academic synthesis and a practical blueprint for how eco-design can help machine tool builders and users deliver improved environmental performance without sacrificing precision, reliability, or competitiveness.

Keywords: Lifecycle assessment, ultra high-performance concrete, life cycle costing, eco-comparison ratio

INTRODUCTION

Machine tools lie at the heart of manufacturing. They shape, cut, mill, grind, and drill workpieces to high precision, enabling the production of components for aerospace, automotive, electronics, and many heavy industries. However, machine tools themselves are often large, heavy, energy-intensive, and long-lived assets. This means they carry significant environmental burdens: from the embodied energy and materials of their manufacture, through large operational energy consumption, to eventual disposal or remanufacturing [1–3].

The goal of this study is to examine how eco-design, also sometimes termed "green design" or "sustainable design", can be applied specifically in the domain of modern machine tool construction. By eco-design, we refer to the systematic integration of environmental considerations into product design phases such that lifecycle impacts (resource use, energy, waste, emissions) are reduced. In the broader literature, this overlaps with fields such as ecomechatronics (the design of mechatronic systems for reduced ecological

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impact), design for manufacture and assembly (DfMA), lifecycle assessment (LCA), and circular economy strategies.

While eco-design has been more extensively applied in consumer goods, construction machinery, and buildings, there is growing research addressing machine tools. For example, a recent review shows that CNC machine tools are characterised by high total energy consumption and low energy efficiency, and thus, there is a need for design optimisation around energy consumption. Another study addresses remanufacturing of conventional grinding machines into CNC tools, showing that remanufacturing is a viable eco-design strategy [4].

Thus, this study synthesises current knowledge into a structured framework of eco-design for machine tool construction and offers pathways for research and industry.

LIFECYCLE STAGES AND ECO-DESIGN LEVERS

In order to apply eco-design effectively, it is helpful to break down the lifecycle of a machine tool into stages and identify levers at each stage where environmental improvements may be achieved [5].

Material and Structural Design

The first stage concerns raw materials (steel castings, cast iron beds, aluminium, composites) and structural design (bed, frame, foundation, cabinet). Key eco - design levers include:

- *Lightweighting/material substitution:* using high-strength alloys, aluminium, or hybrid materials (e.g., ultra-high-performance concrete for machine tool beds) to reduce raw material and embodied energy. For instance, research shows that using ultra-high-performance concrete (UHPC) in machine tool housing can reduce material usage and improve precision [6, 7].
- *Modular structural design:* enabling component replacement instead of whole asset replacement. Modular beds, heads, and control systems can extend useful life. For example, a "green reconfigurable NC machine tool" design emphasised modularity for deep - hole components.
- *Design for disassembly/recyclability:* design parts so that at the end of life, they can be separated, refurbished, and recycled. The green design and manufacturing method for construction machinery emphasises the selection of green materials and manufacturing technologies for resource efficiency.

Manufacture and Assembly

During the assembly and commissioning stage, eco-design levers include:

- *Efficient manufacturing processes:* minimising waste, adopting lean manufacture, using additive manufacturing for near-net shapes, and planning for simple assembly (DfMA) to reduce energy and labour.
- *Modular assembly:* enabling easier upgrades, retrofits, and remanufacturing.
- *Embedded sensors and mechatronic design:* fewer moving parts, better integration of control electronics to reduce energy losses in idle states.

Operation/Use Phase

The use phase is where machine tools often consume the majority of their energy and resources over their lifetime. Eco-design levers here are crucial:

- *Energy-efficient drives, motors and auxiliary systems:* selecting high-efficiency electric motors, optimising hydraulics/pneumatics, variable frequency drives, regenerative braking [8].
- *Optimised machine structure and dynamics:* reducing machine mass, friction, and inertia, thus lowering the required power. There is increasing research on energy-consumption modelling of CNC machine tools: one recent paper reviews methods of analysing energy consumption, structural optimisation, and evaluation methods.
- *Intelligent control and idle-state energy management:* using sensors to detect idle periods and switch off or reduce power; predictive maintenance to avoid inefficient operation; digital twin monitoring to optimise performance.

- *Machine tool utilisation and scheduling:* maximising productive time, avoiding under - utilisation, which reduces environmental efficiency per part.
- *Retrofitting and upgrading rather than replacement:* for example, remanufacturing a conventional milling machine into a CNC version may yield environmental benefits by reducing raw input and emissions compared to a full new build.

Maintenance, Upgrade, and Remanufacture

- *Modular upgradeability:* designing heads, drives, and control systems to be swapped out as technology improves, rather than entire machine replacement. The "green modular design" oriented for construction machinery describes the evaluation of "green degree" and "module degree" using modern design tools.
- *Remanufacturing and refurbishment:* machines can be returned, refurbished, upgraded, and redeployed. The multi - criteria assessment of remanufacturing conventional grinding machines into CNC machine tools is a good example of decision-making for remanufacture.
- *Lifecycle costing and decision support:* Eco-design demands that the economic dimension be included alongside the environmental. Tools developed for buildings (e.g., eco-design tool with circularity information) could be adapted to machine tools [9].

End-of-Life/Recycling

At the end of useful life, machine tools should be designed for:

- Disassembly, sorting, and recyclability of materials.
- Reuse of major subassemblies (spindle units, drives) in other machines.
- *Material recovery:* cast iron, steel, and aluminium should be recycled, ideally at a high recovery rate.
- *Circular economy business models:* leasing, take - back schemes, and service models that encourage reuse rather than disposal.

KEY ECO-DESIGN STRATEGIES FOR MACHINE TOOLS

Below, we discuss specific strategies aligned with the lifecycle levers.

Lightweight and Hybrid Materials

Using advanced materials and structural design to reduce mass and embodied energy. For example, the UHPC study for machine tool housing demonstrated that ultra-high-performance concrete offered high strength, low porosity, and corrosion resistance, thereby both enhancing precision and offering recyclability benefits. Hybrid structures (e.g., combining cast iron with composites or polymer concrete) allow vibration damping and lower inertia, thus reducing required drive power and improving dynamic performance.

By reducing the mass of beds and supports, one also reduces foundation demands, energy for moving masses, and thus operational energy. However, substitution must not compromise stiffness, accuracy, and dynamic behaviour, essential for machine tools [10].

Modular, Reconfigurable Architecture

Designing machine tools with a modular architecture means that as technology evolves (for example, new spindle motors, new control electronics, new tool changers), modules can be replaced instead of discarding the entire machine. The "green reconfigurable NC machine tool" study emphasised module design of bed module, head module, cutting-tool auxiliary system, and numerical control system for improved adaptability.

Remanufacturing studies show that conventional machines can be converted to higher-axis CNC machines with a significant remanufacturability index (0.637 to 0.999) in the example of conventional surface grinding machines being upgraded.

Such modular upgradeability allows machine tool builders and users to extend asset life, reduce the demand for raw materials, and reduce waste.

Energy-Efficient Drives and Systems

One of the major operational burdens of machine tools is energy consumption in drives, hydraulics, cooling/lubrication systems, vacuum/chip extraction, and idle states. The recent review in Sustainability (2024) shows the component breakdown of energy consumption in CNC machine tools and highlights modelling, structural optimisation, and evaluation methods.

Design Strategies

- Using high-efficiency electric motors (IE3/IE4 classes) and appropriate drive electronics.
- Variable frequency drives and regenerative drives that recover kinetic energy.
- Efficient chip removal and coolant systems (minimising auxiliary power).
- Optimising axis drive dynamics (mass, inertia) to minimise energy per part cut.
- Smart standby/idle modes and sensor-based shutdown when no load is present.

All these reduce operational energy, which over the long life of a machine tool often dominates the environmental footprint.

Digitalisation, Monitoring and Predictive Maintenance

Eco-design increasingly means “smart” design, embedding sensors and connectivity to monitor energy use, machine health, vibration, load cycles, and enabling predictive maintenance. This avoids unnecessary downtime, inefficient operation, redundant idling, and maximises productive utilisation of the asset.

Digital twin models may help machine tool builders and owners simulate life-cycle energy consumption, schedule maintenance to maintain optimal efficiency, and plan for end-of-life reversal. Thus, smart design combined with sustainability design leads to higher operational eco-performance.

Lifecycle Assessment and Decision Support

Design decisions need to be supported by data: material choices, energy use, recyclability, and maintenance costs. Lifecycle assessment (LCA) and life cycle costing (LCC) are essential tools. For machine tools, though less common than buildings, papers point out the need for modelling energy consumption, structural optimisation, and evaluation methods.

Remanufacturing case studies illustrate the need for multi - criteria decision models (cost, time, accuracy, reliability, complexity) to evaluate upgrade paths.

Designers and machine tool OEMs should embed eco-design tools early in the design phase, selecting materials and modules not just for performance but for energy, resource use, upgradeability, and end-of-life.

Circular Economy Business Models

Beyond technical design, machine tool manufacturers and users can adopt circular economy models: leasing of machine tools, take-back programmes, remanufacturing services, swapping modules instead of scrapping machines, and second-life use of drives, spindles, and electronics. The eco-design for construction machinery literature emphasises green material selection and manufacturing technologies, but the model applies equally to machine tools.

CASE EXAMPLES AND RESEARCH FINDINGS

Remanufacturing of Conventional Milling Machines

A case study converting a conventional milling machine into a CNC version assessed input material, energy, and CO_2 emissions; the authors introduced an “eco-comparison ratio (ECR)” to compare remanufacturing vs. new build. The findings highlight that remanufacturing can significantly reduce embodied energy and emissions, demonstrating the importance of upgradeability and reuse in machine tool fleets.

Energy-Consumption Optimisation of CNC Machine Tools

The 2024 review article in Sustainability shows how machine tool energy consumption can be broken down, modelled, and optimised. Key findings: most machine tool energy is consumed in non - cutting idle states and in auxiliary systems; structural and parametric optimisation of subsystems (spindle, feed drives) leads to measurable energy savings; yet the research is still fragmented.

Green Design and Modular Methods in Construction Machinery

While not machine tools per se, the methods applied to construction machinery have direct relevance: e.g., the "design method on green modular that oriented construction machinery" studied the evaluation of green degree and module degree via AHP and fuzzy methods. The approach is directly translatable to machine tool modularity: evaluating how modular design increases sustainability by enabling reuse, replacement, and less waste.

BARRIERS, CHALLENGES, AND ENABLERS

Implementing eco-design in machine tool construction faces several barriers:

- *Cost:* Advanced materials, modular architecture, sensors, and smart control often involve a higher upfront cost. The business case must account for lifecycle savings.
- *Standards and certification:* Unlike building and consumer goods, machine tools lack standardised eco-design frameworks or lifecycle assessment databases tailored for them.
- *Data availability:* LCA and energy-use data for machine tools are still limited; this creates uncertainty in decision support.
- *Behaviour and business model inertia:* Machine tool users often replace entire machines rather than upgrade; OEMs may lack incentive to design for modularity and remanufacture.
- *Precision and accuracy constraints:* Machine tools must meet demanding accuracy, stiffness, and dynamic performance; eco-design must not compromise these.
- *Longevity and amortisation:* Machine tools may be in service for decades; predicting future upgradeability, reuse, and energy savings is complex.

Enablers and strategies to overcome these include:

- Embedding eco-design goals from the earliest design phase (e.g., material selection, modular architecture, upgrade path).
- Developing energy-consumption models and digital twins to provide measurable business cases for energy savings.
- Offering upgrade and remanufacture services as part of a service - based business model, enabling circular economy benefits.
- Collaboration industrywide to develop databases of material-use, embodied energy, and energy consumption profiles of machine tool subsystems.
- Government incentives, regulation, or customer demand could push OEMs and users toward higher sustainability standards.

PROPOSED ROADMAP FOR IMPLEMENTATION

For machine tool manufacturers and users seeking to implement eco-design, a roadmap is proposed:

1. *Audit and baseline:* Determine current lifecycle energy consumption, material use, existing machine stock, and potential upgrade paths.
2. *Define eco-design targets:* Set measurable targets for embodied energy reduction, operational energy intensity (kWh per piece), modular upgrade rate, and recyclability percentage.
3. *Design phase integration:* During machine tool design, include materials specialists, lifecycle engineers, and digital twin modelers. Use multi - criteria decision tools to compare alternative modules and materials based on performance and sustainability metrics.

4. *Modular architecture development:* Define common interfaces, module exchangeability (spindle module, control module, drive module). Design for disassembly and upgrade.
5. *Energy efficient subsystems:* Optimize drive systems, idle modes, auxiliary systems; model axis dynamics and optimise mass/inertia; implement sensor networks for runtime monitoring.
6. *Lifecycle monitoring:* Use sensors and a digital twin to monitor actual energy usage, maintenance events, idle time, utilisation; feed data back to design improvements.
7. *Upgrade/remanufacture strategy:* Offer or plan for remanufacture or module replacement rather than full replacement; document and track disposed machines and modules for reuse or recycling.
8. *End-of-life planning:* Design parts for disassembly, label materials/subassemblies, enable recycling or refurbishing; track recovery rates.
9. *Business model alignment:* Align incentives, for instance, leasing machine tools, service contracts with guaranteed energy performance, and take-back programmes to encourage the circular economy.
10. *Continuous improvement:* Collect data, refine models, update LCA and LCC calculations, benchmark best practices across industry.

CONCLUSION

Eco-design in machine tool construction is both necessary and feasible. Given the longevity, energy intensity, and material demands of machine tools, even relatively modest improvements in design, modularity, materials, and operational efficiency can yield significant sustainability benefits over the lifecycle. The literature, while still emerging, provides promising case studies and methods, from energy-consumption modelling of CNC machine tools, to remanufacturing conventional machines, to modular "green" machine tool design. The path forward requires integration of sustainability criteria early in design, adoption of modular/upgradable architecture, digital monitoring for operational optimisation, and business models that support circulation, reuse, and remanufacture. The barriers of cost, standards, and data availability must be addressed through industry collaboration, government incentives, and innovation.

For machine tool manufacturers, the imperative is clear: precision and performance remain non-negotiable, but environmental performance must become intrinsic. For users, choosing machine tools designed with eco-principles, maximising utilisation, and keeping machines in service via upgrades rather than replacement offers environmental and economic upside.

In conclusion, eco-design for machine tools is not a "nice-to-have"; it is a strategic lever for sustainable manufacturing in the 21st century. Future research should further refine lifecycle assessment tools specific to machine tools, develop standardised eco-design criteria, and pilot industry-academia collaborations to validate modular, upgradeable machine tool architectures at scale.

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