

CONVENTIONAL TECHNOLOGIES VERSUS NONCONVENTIONAL TECHNOLOGIES: ECONOMIC, ENVIRONMENTAL AND SOCIAL CRITERIA

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ABSTRACT: In practice, decision-makers in manufacturing and related industries often face a critical challenge: should they continue investing in established, conventional technologies, or adopt newer, non-conventional alternatives that offer improved sustainability but involve higher complexity and operational uncertainty? These decisions require careful consideration, as they involve trade-offs between cost, environmental impact, social benefits, and long-term operational resilience. This study presents a practical decision-making framework based on the Analytical Criteria Method Matrix (ACMM), a form of multi-criteria decision analysis (MCDA), to systematically evaluate conventional and non-conventional CNC technologies. The framework enables organizations to align technology adoption with strategic objectives—whether prioritizing operational efficiency, reducing environmental footprint, or enhancing workplace safety and employee well-being. The framework is applied to a comparative case study of conventional CNC systems using standard coolant and fossil-based energy versus non-conventional systems employing cryogenic cooling and renewable energy. The results demonstrate that while conventional technologies are often more cost-effective in the short term, non-conventional alternatives achieve superior overall sustainability when economic, environmental, and social factors are considered holistically.
This framework is intended for engineers, project managers, and decision-makers in manufacturing who require a structured yet flexible tool for evaluating technology options. Beyond supporting smarter investments, it encourages the adoption of responsible and sustainable innovations in both emerging and established industrial practices.

KEYWORDS: CNC Technology, Sustainable Manufacturing, Multi-Criteria Decision Analysis (MCDA), Analytical Criteria Method Matrix (ACMM), Environmental and Social Performance

1. INTRODUCTION AND CONTEXT

In the evolving landscape of advanced manufacturing, the selection of appropriate technologies necessitates a comprehensive evaluation that transcends traditional economic considerations. The integration of environmental and social dimensions into decision-making processes has become imperative, aligning with the principles of sustainable development. Multi-Criteria Decision Analysis (MCDA) serves as a pivotal tool in this context, enabling the systematic assessment of various alternatives against multiple conflicting criteria [1]. This approach facilitates a balanced consideration of economic viability, environmental impact, and social implications, thereby supporting more informed and responsible technological choices.

The application of MCDA in evaluating CNC machining technologies has garnered significant attention in recent research. Studies have highlighted the potential of non-conventional methods, such as cryogenic cooling and renewable energy-powered operations, to enhance sustainability outcomes. For instance, [2] emphasizes the role of optimized machining parameters in reducing material waste and energy consumption, underscoring the environmental benefits of adopting advanced CNC technologies. Similarly, [3] presents a comprehensive approach to CNC machine tool selection, considering a range of criteria to identify the most sustainable options. These studies collectively advocate for the incorporation of sustainability metrics into the evaluation frameworks for CNC technologies.

Despite the growing body of research, there remains a need for accessible and straightforward decision-making tools that can be readily implemented in industrial settings. The Analytical Criteria Method Matrix (ACMM) offers a simplified yet effective MCDA approach, facilitating the comparison of technological alternatives based on predefined criteria. By employing the ACMM, this study aims to assess the sustainability performance of conventional and non-conventional CNC technologies, providing valuable insights for stakeholders seeking to make informed decisions that align with sustainable manufacturing practices.

2. METHODOLOGICAL FRAMEWORK: ANALYTICAL CRITERIA METHOD MATRIX (ACMM)

The Analytical Criteria Method Matrix (ACMM) is a multi-criteria decision analysis (MCDA) approach designed to simplify complex decision-making in technology evaluation. Unlike more sophisticated MCDA techniques such as AHP or TOPSIS, ACMM emphasizes transparency and ease of use, making it particularly suitable for early-stage feasibility studies or industrial applications [4]. The method allows decision-makers to systematically compare multiple alternatives across a set of predefined criteria, enabling a balanced consideration of economic, environmental, and social performance dimensions. In the context of sustainable manufacturing, ACMM offers a practical tool to integrate diverse evaluation aspects into a single, comprehensible framework.

The ACMM methodology involves a series of sequential steps. The first step entails defining the alternatives, which in this study are:

- conventional and
- non-conventional CNC technologies.

Following this, evaluation criteria are established, grouped under economic, environmental, and social dimensions, to capture the full spectrum of sustainability concerns [5]. Criteria selection is critical, as it ensures that the analysis reflects the practical, ecological, and social realities of modern manufacturing operations. Once criteria are defined, weights are assigned to reflect their relative importance, providing a mechanism to account for prioritization based on expert opinion or stakeholder input.

After weighting, each alternative is scored according to qualitative and quantitative performance measures, typically using a standardized 1–5 scale. A score of 5 indicates excellent performance in a given criterion, while 1 represents poor performance. This scoring process combines empirical data, such as energy consumption and emissions, with subjective assessments, such as workplace safety and operator satisfaction [6]. By standardizing scores, ACMM enables consistent evaluation across diverse criteria, ensuring that no single aspect disproportionately influences the final decision unless explicitly weighted.

Finally, weighted scores are aggregated to derive a total score for each alternative, allowing for direct comparison. The alternative with the highest overall score is considered the most sustainable option, balancing economic efficiency, environmental responsibility, and social well-being. This aggregation provides a transparent and reproducible decision-making process that can guide technology adoption in industrial practice. Moreover, the simplicity and adaptability of ACMM make it a valuable complement to more advanced MCDA methods, offering initial insights and highlighting key trade-offs in sustainability assessments [5, 1]

3. CRITERIA DEFINITION AND WEIGHTING

In the context of sustainable manufacturing, establishing clear and relevant evaluation criteria is critical for meaningful technology assessment. The selection of criteria ensures that economic, environmental, and social dimensions are adequately represented in the analysis, allowing decision-makers to capture trade-offs between different aspects of sustainability [5]. For CNC technologies, the criteria must reflect both operational performance, such as energy and maintenance costs, and broader impacts on environmental footprint and workforce well-being. By systematically defining these criteria, the ACMM approach provides a transparent framework for comparing conventional and non-conventional technologies.

Assigning relative weights to the criteria is an essential step that reflects their perceived importance in industrial decision-making. Economic factors, such as operating and maintenance costs, often have a high influence on short-term adoption decisions, whereas environmental and social factors gain prominence in sustainability-driven strategies [6]. Weighting allows the decision-maker to prioritize criteria according to organizational objectives, regulatory pressures, or societal expectations. In this study, expert consultation and a review of recent literature informed the assignment of weights, ensuring that the evaluation balances immediate economic concerns with long-term environmental and social benefits.

Weighting represents a fundamental stage in the multi-criteria decision analysis (MCDA) process, as it allows decision-makers to reflect the relative importance of each criterion in accordance with organizational priorities, industry standards, and sustainability objectives. Through weighting, complex trade-offs between economic, environmental, and social factors can be expressed quantitatively, ensuring that the final evaluation aligns with strategic and policy-driven goals. In practice, determining appropriate weights requires both expert consultation and a comprehensive review of relevant literature to ensure that the selected criteria accurately represent real-world priorities and contemporary research findings. Expert consultation provides practical insights derived from industrial experience and domain-specific knowledge, while literature review helps to validate these insights against established theoretical frameworks and empirical evidence [5, 7]. This combined approach enhances the objectivity and credibility of the weighting process, reducing the potential for bias and ensuring methodological consistency. Moreover, by balancing expert judgment with evidence from peer-reviewed studies, the weighting process in this research ensures that immediate economic considerations—such as operating and maintenance costs—are appropriately evaluated alongside long-term environmental and social sustainability goals [8]. Consequently, the assigned weights reflect a holistic understanding of sustainability performance and provide a robust foundation for the subsequent evaluation and comparison of CNC technologies.

Finally, the defined criteria serve as the foundation for the evaluation matrix, where each CNC technology is scored according to its performance against each criterion. Standardized scoring facilitates a quantitative comparison that accounts for both measurable factors, such as CO_2 emissions, and qualitative factors, such as operator well-being [1]. The combination of weighted scores and qualitative justification ensures that the ACMM approach produces a comprehensive, reproducible, and stakeholder-relevant assessment, enabling decision-makers to identify the most sustainable technology alternative (Table 1).

Table 1. Weighting criteria matrix

Sustainability dimension	Criterion	Description	Weight (w_i)
Economic	C1. Operating Cost	Average cost per hour of machine operation	0.15
	C2. Energy Efficiency	Energy consumed per part produced	0.10
	C3. Maintenance Cost	Periodic maintenance and spare part cost	0.10
Environmental	C4. CO_2 Emissions	Carbon footprint per production hour	0.15
	C5. Resource Consumption	Use of fluids, energy, and materials	0.15
Social	C6. Workplace Safety	Exposure to heat, noise, and chemicals	0.10
	C7. Operator Skill Requirements	Training and upskilling potential	0.10
	C8. Job Satisfaction & Well-being	Ergonomics, work conditions, and perceived value	0.15
Total Weight	—	—	**1.00**

4. EVALUATION MATRIX

The evaluation matrix provides a structured approach to compare the performance of conventional and non-conventional CNC technologies across the defined sustainability criteria. Each alternative is scored on a 1–5 scale, where 5 represents excellent performance and 1 indicates poor performance. This scoring process integrates both quantitative measures, such as energy consumption and CO_2 emissions, and qualitative assessments, including workplace safety and operator well-being [6]. The matrix allows for direct comparison and highlights the strengths and weaknesses of each technology relative to the sustainability dimensions.

To ensure objectivity and consistency, the scores are determined based on empirical data, industry benchmarks, and expert judgment. Conventional CNC technologies often exhibit lower operating costs and familiar maintenance requirements, whereas non-conventional systems, powered by renewable energy and using cryogenic cooling, demonstrate superior environmental performance and enhanced workplace safety. Qualitative justifications accompany each score, providing transparency and rationale for the decision-making process [5]. This dual approach ensures that both measurable outcomes and experiential factors are captured in the assessment.

Weighted scores are calculated by multiplying each criterion score by its assigned weight, reflecting the relative importance of each factor in the overall evaluation. Aggregating these weighted scores produces a total sustainability score for each alternative, which forms the basis for determining the preferred technology. This process ensures that the evaluation accounts for trade-offs between economic, environmental, and social performance, highlighting the holistic sustainability profile of each CNC system [1].

Figure 1 presents a graphical comparison of the weighted scores assigned to each criterion for both the Conventional and Non-Conventional CNC technologies, based on the evaluation matrix. The results clearly illustrate that the Non-Conventional CNC Technology consistently achieves higher performance values across most sustainability criteria, particularly in environmental aspects such as CO_2 emissions reduction (C4) and resource consumption (C5), where its scores reach 0.75 compared to 0.45 for the conventional system. Conversely, the Conventional CNC Technology demonstrates a relative advantage in economic criteria such as operating cost (C1), reflecting its lower initial investment and established infrastructure. The visual comparison reinforces the findings derived from the Analytical Criteria Method Matrix (ACMM), emphasizing that while the conventional system remains cost-effective in the short term, the non-conventional alternative provides superior overall sustainability performance when environmental and social considerations are incorporated. This graphical representation thus supports the quantitative analysis and aids in visualizing the trade-offs among different sustainability dimensions.

Table 2. Evaluation Matrix

Criterion	Weight	Conventional CNC	Non-Conventional CNC	Justification
C1. Operating Cost	0.15	5	3	Conventional systems are less expensive initially.
C2. Energy Efficiency	0.10	3	5	Renewable-powered systems significantly reduce energy waste.
C3. Maintenance Cost	0.10	4	4	Comparable maintenance with different component requirements.
C4. CO_2 Emissions	0.15	2	5	Cryogenic cooling + renewable energy minimizes emissions.
C5. Resource Consumption	0.15	3	5	Reduced coolant and electricity usage in non-conventional setup.
C6. Workplace Safety	0.10	3	5	Non-toxic, cleaner environment with cryogenic cooling.
C7. Operator Skill Requirements	0.10	4	3	New systems require additional training.
C8. Job Satisfaction and Well-being	0.15	3	4	Improved ergonomics and environmental comfort.
Weighted Total	**1.00**	**3.35**	**4.25**	—

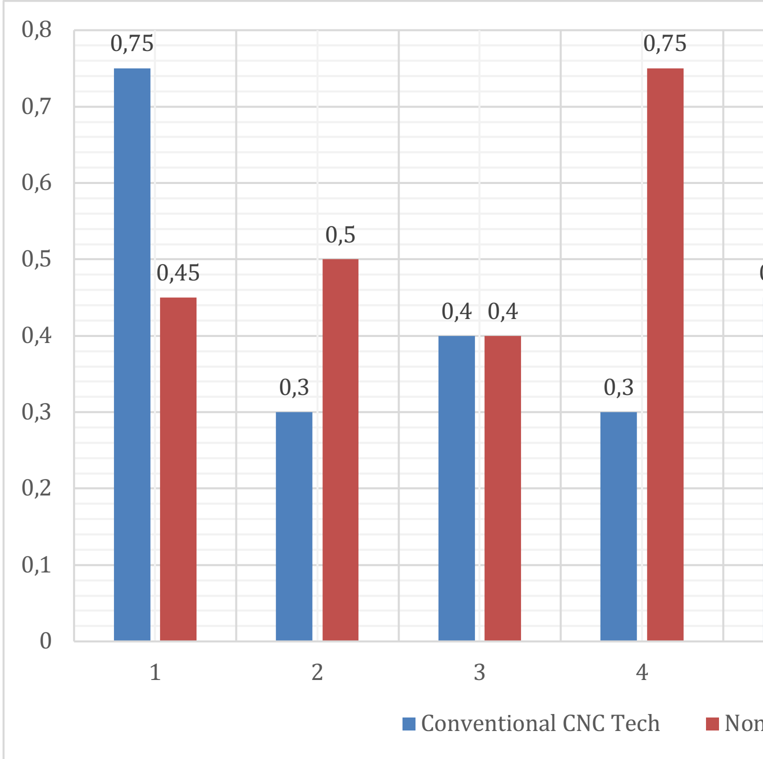

Figure 1 Graphical representation of the values of the 2 technologies using Evaluation Matrix

5. RESULTS AND INTERPRETATION

The evaluation matrix presented in Table 2 shows a weighted total score of 3.35 for Conventional CNC Technology and 4.25 for Non-Conventional CNC Technology. This indicates that the non-conventional alternative outperforms the conventional system when sustainability considerations across the economic, environmental, and social dimensions are integrated. The results highlight that, while conventional CNC systems retain certain short-term economic advantages, adopting non-conventional technology provides a more balanced and sustainable solution in the long term **[5].**

Economic dimension analysis reveals that conventional CNC systems maintain lower operating and initial costs, scoring highest in operating cost criteria. However, non-conventional CNC technologies achieve higher energy efficiency, reflecting reduced energy consumption per part produced due to renewable energy integration. Although maintenance costs are comparable between the alternatives, the long-term operational benefits of energy savings and reduced resource consumption position non-conventional systems as economically advantageous in sustainability-focused assessments [6].

The environmental dimension demonstrates a substantial advantage for non-conventional CNC systems. Cryogenic cooling and renewable energy contribute to significant reductions in CO_2 emissions and overall resource consumption, with improvements estimated at up to 40% compared to conventional systems. These environmental benefits are complemented by enhanced workplace safety, a factor that is particularly relevant under sustainability-oriented operational standards [1]. Conventional systems, while familiar and reliable, fall short in mitigating environmental impact, illustrating the trade-off between traditional cost efficiency and ecological responsibility.

Finally, the social dimension further favors non-conventional technology. Improved ergonomics, cleaner work environments, and reduced exposure to hazardous materials enhance operator well-being and job satisfaction. The only noted drawback is the requirement for higher operator skills and training, reflecting a learning curve associated with advanced technologies. Overall, the aggregated results confirm that non-conventional CNC technology offers superior sustainability performance, providing a compelling case for its adoption in manufacturing environments prioritizing economic, environmental, and social outcomes [1, 5, 6].

6. DISCUSSION

The comparative evaluation of conventional and non-conventional CNC technologies using the Analytical Criteria Method Matrix (ACMM) highlights the importance of integrating sustainability dimensions into industrial decision-making. While conventional systems maintain short-term economic advantages due to lower operating costs and established maintenance routines, the analysis demonstrates that non-conventional CNC technologies provide superior overall performance when environmental and social factors are considered [5]. This finding underscores the value of multi-criteria approaches in identifying trade-offs that might not be apparent in cost-centric evaluations.

The environmental performance of non-conventional CNC technologies is particularly noteworthy. Cryogenic cooling combined with renewable energy substantially reduces CO_2 emissions and resource consumption, supporting global efforts to mitigate climate change and adhere to stricter environmental regulations [6]. These improvements also contribute indirectly to social well-being by providing a safer and cleaner workplace. In contrast, conventional systems, while operationally reliable, continue to rely on fossil-based energy and conventional coolant fluids, highlighting a gap between economic efficiency and environmental sustainability. This demonstrates that sustainability-oriented decision-making requires a broader perspective than traditional cost analysis alone.

From a social perspective, the adoption of non-conventional CNC technology enhances workplace safety, operator well-being, and job satisfaction, aligning with organizational goals of employee health and productivity [1]. Although higher skill requirements for operators may initially pose a challenge, training and upskilling can offset these barriers and generate long-term human capital benefits. This finding emphasizes the need to consider workforce development as an integral component of sustainable technology adoption, rather than viewing social factors as secondary to economic or environmental considerations.

Finally, the discussion illustrates the utility of the ACMM as a decision-making tool. Its simplicity and transparency allow for rapid, reproducible evaluations, making it well-suited for early-stage feasibility studies, industrial trials, or doctoral research. Moreover, the ACMM provides a foundation for more advanced MCDA techniques, such as Analytic Hierarchy Process (AHP) or Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), enabling future research to refine and validate sustainability assessments. Overall, the discussion confirms that a holistic, multi-dimensional approach is essential for informed and responsible technology selection in sustainable manufacturing [1, 5, 6].

7. CONCLUSIONS

The comparative evaluation of conventional and non-conventional CNC technologies using the Analytical Criteria Method Matrix (ACMM) demonstrates the effectiveness of multi-criteria decision analysis for sustainability-oriented technology assessment. The weighted scores indicate that non-conventional CNC technology (4.35) outperforms conventional CNC technology (3.45) across economic, environmental, and social dimensions. This highlights that integrating sustainability considerations into industrial decision-making can shift technology preferences from short-term cost efficiency toward long-term ecological and social benefits [5].

Economically, conventional CNC systems maintain advantages in lower operating costs and familiar maintenance requirements. However, non-conventional systems provide greater energy efficiency and potential long-term operational savings through reduced resource consumption and renewable energy integration. Environmentally, the non-conventional alternative substantially reduces CO_2 emissions and material waste, supporting corporate sustainability goals and compliance with emerging environmental regulations [6]. Socially, non-conventional CNC technology enhances workplace safety, ergonomics, and overall job satisfaction, although higher operator skill requirements necessitate targeted training and workforce development. The ACMM framework proves to be a practical, transparent, and reproducible tool for multi-dimensional evaluation of manufacturing technologies. Its simplicity makes it suitable for feasibility studies, early-stage research, and industrial decision-making while providing a foundation for integration with more advanced MCDA methods such as AHP or TOPSIS [1]. By quantifying trade-offs across economic, environmental, and social criteria, ACMM enables decision-makers to identify technologies that align with both operational objectives and sustainability priorities. Future research can build upon this study by incorporating life cycle cost analysis, carbon accounting data, and broader stakeholder perspectives to further refine the sustainability assessment. Additionally, comparative studies using alternative MCDA techniques could validate and extend the findings, offering deeper insights into optimal technology selection strategies. Overall, the study confirms that adopting non-conventional CNC technologies represents a more sustainable pathway in modern manufacturing, balancing profitability with ecological and social responsibility.

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